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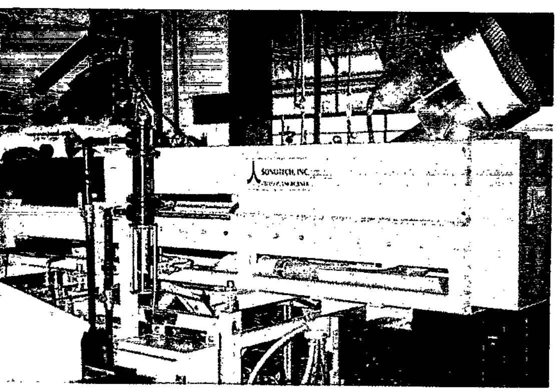
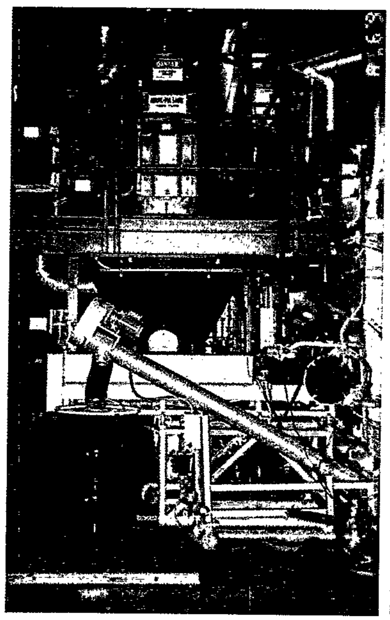
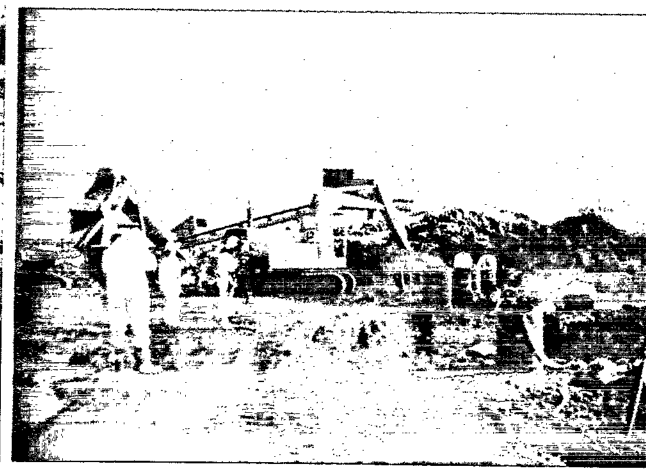
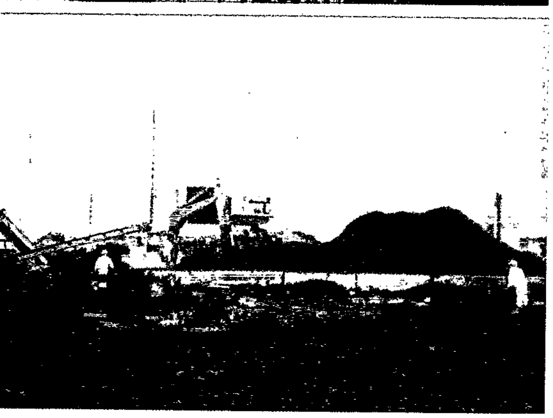
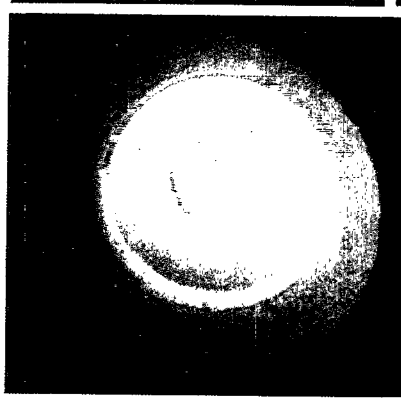
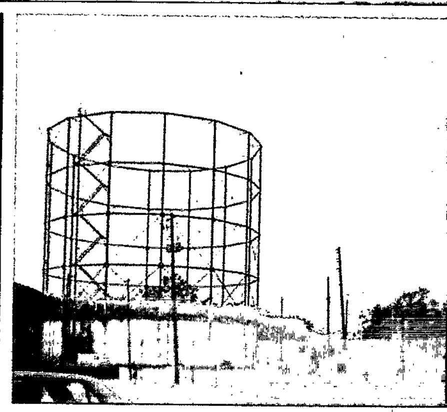
EPA

Sonotech, Inc. Frequency-Tunable Pulse Combustion System (Cello® Pulse Burner)

Innovative Technology Evaluation Report

SITE
SUPERFUND INNOVATIVE
TECHNOLOGY EVALUATION

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Innovative Technology Evaluation Report

National Risk Management Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

Notice

This document has been prepared for the U.S. Environmental Protection Agency (EPA) Superfund Innovative Technology Evaluation (SITE) program under Contract No. 68-C5-0037. This document has been subjected to EPA's peer and administrative reviews and has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute an endorsement or recommendation for use.

Foreword

The EPA is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet these mandates, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the EPA center for investigation of technical and management approaches for reducing risks from threats to human health and the environment. The focus of the NRMRL research program is on methods for the prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites and groundwater; and prevention and control of indoor air pollution. The goals of this research effort are to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

This publication has been produced as part of the NRMRL strategic, long-term research plan. It is published and made available by the EPA Office of Research and Development to assist the user community and to link researchers with their clients.

E. Timothy Oppelt, Director
National Risk Management Research Laboratory

Abstract

Sonotech, Inc. (Sonotech) of Atlanta, GA, has developed a pulse combustion burner technology that claims to offer benefits when applied in a variety of combustion processes. The technology incorporates a combustor that can be tuned to induce large-amplitude acoustic or sonic pulsations inside combustion process units, such as boilers or incinerators. This report summarizes the findings of an evaluation of the pulse combustion burner system developed by Sonotech. The Cello® Pulse Burner system was demonstrated in the autumn of 1994 at the EPA Incineration Research Facility (IRF) in Jefferson, AR, under the EPA SITE program.

The information is intended for remedial managers, environmental consultants, and other potential users who may consider using the technology to treat Superfund and Resource Conservation and Recovery Act of 1976 (RCRA) hazardous wastes. It presents an overview of the SITE program, describes the Sonotech system, and lists key contacts; discusses information relevant to the technology's application, including an assessment of the technology related to the nine feasibility study evaluation criteria, potential applicable environmental regulations, and operability and limitations of the technology; summarizes the costs associated with implementing the technology; presents the waste characteristics, demonstration approach, demonstration procedures, and the results and conclusions of the demonstration; summarizes the technology status; and includes a list of references. The Appendix presents case studies provided by the developer.

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Acronyms and Abbreviations

Acurex	Acurex Environmental Corporation
AEERL	Air and Energy Engineering Research Laboratory
APCD	Air pollution control device
APCS	Air pollution control system
ARAR	Applicable or relevant and appropriate requirement
ATTIC	Alternative Treatment Technology Information Center
BIF	Boilers and industrial furnace
BTEX	Benzene, toluene, ethylbenzene, and xylenes
Btu	British thermal unit
Btu/hr	British thermal unit per hour
Btu/lb	British thermal unit per pound
C	Carbon
CAA	Clean Air Act
$CaCO_3$	Calcium carbonate
CaO	Calcium oxide
°C	Degree Celsius
CEM	Continuous emissions monitor
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CERI	Center for Environmental Research Information
CFR	Code of Federal Regulations
Cl	Chlorine
CO	Carbon monoxide
CO_2	Carbon dioxide
CVAAS	Cold Vapor Atomic Absorption Spectroscopy
dB	Decibel
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
DRE	Destruction and removal efficiency
dscf/hr	Dry standard cubic foot per hour
EPA	U.S. Environmental Protection Agency
°F	Degree Fahrenheit
ft^3	Cubic foot
gc/ms	Gas Chromatography/Mass Spectrometry
GFAAS	Graphite Furnace Atomic Absorption Spectroscopy
grain/dscf	Grain per dry standard cubic foot
g/hr	Gram per hour
gpm	Gallon per minute
GRI	Gas Research Institute
H	Hydrogen
HDPE	High-density polyethylene
HEPA	High-efficiency particulate air
Hz	Hertz or cycles per second
IC	Ion chromatography
ICP	Inductively coupled argon plasma spectroscopy
IRF	U.S. EPA Incineration Research Facility

Acronyms and Abbreviations (continued)

ITER	Innovative Technology Evaluation Report
kBtu/hr	Thousand British thermal units per hour
kg	Kilogram
kg/hr	Kilograms per hour
kPa	Kilopascal
kW	Kilowatt
kWh	Kilowatt hour
lb/hr	Pound per hour
LDR	Land disposal restrictions
L/min	Liter per minute
m^3	Cubic meter
MBtu	Million British thermal units
MDL	Method detection limit
mg/dscm	Milligram per dry standard cubic meter
mg/hr	Milligram per hour
mg/kg	Milligram per kilogram
mg/L	Milligrams per liter
MGP	Manufactured gas plant
MJ	Megajoule
MJ/kg	Megajoule per kilogram
MS	Matrix spike
MSD	Matrix spike duplicate
mv	Millivolt
N	Nitrogen
NAAQS	National Ambient Air Quality Standards
ng/dscm	Nanogram per dry standard cubic meter
NO_x	Nitrogen oxide
NRMRL	National Risk Management Research Laboratory
NSPS	New Source Performance Standard
O_2	Elemental oxygen
ORD	U.S. EPA Office of Research and Development
OSHA	Occupational Safety and Health Administration
OSWER	U.S. EPA Office of Solid Waste and Emergency Response
PAH	Polynuclear aromatic hydrocarbon
PCDD	Polychlorinated dibenzo-p-dioxin
PCDF	Polychlorinated dibenzofuran
PCB	Polychlorinated biphenyl
PE	Polyethylene
Peoples	Peoples Natural Gas Company Superfund site in Dubuque, IA
POHC	Principal organic hazardous constituent
PPE	Personal protective equipment
ppm	Part per million
PRC	PRC Environmental Management, Inc.
PSD	Prevention of significant deterioration
QA	Quality assurance
QAPP	Quality assurance project plan
QC	Quality control
RCRA	Resource Conservation and Recovery Act of 1976
RKS	Rotary kiln incineration system
RPD	Relative percent difference
rpm	Revolutions per minute
S	Sulfur
SARA	Superfund Amendments and Reauthorization Act of 1986
SBIR	Small Business Innovative Research
SITE	Superfund Innovative Technology Evaluation
Sonotech	Sonotech, Inc. of Atlanta, GA

Acronyms and Abbreviations (continued)

SVOC	Semivolatile organic compound
TCLP	Toxicity characteristic leaching procedure
TEF	Toxicity equivalency factors
TEQ	2,3,7,8-TCDD equivalents
TOC	Total organic carbon
TSCA	Toxic Substances Control Act
TSD	Treatment, storage, or disposal
TRL	Target reporting limit
TUHC	Total unburned hydrocarbons
μg/dscm	Microgram per dry standard cubic meter
μg/L	Microgram per liter
VISITT	Vendor Information System for Innovative Treatment Technologies
VOC	Volatile organic compound
VOST	Volatile organic sampling train
2,3,7,8-TCDD	2,3,7,8-Tetrachlorodibenzo-para-dioxin

Acknowledgements

This report was prepared under the direction of Ms. Marta K. Richards, the EPA SITE project manager with NRMRL in Cincinnati, OH. This report was prepared by Mr. Anthony Gardner, Dr. Kenneth Partymiller, Mr. Jeffrey Swano, and Ms. Regina Bergner of PRC Environmental Management, Inc. (PRC), and Drs. Shyam Venkatesh and Larry Waterland of Acurex Environmental Corporation (Acurex). Contributors and reviewers for this report included Ms. Marta K. Richards of NRMRL and Mr. Zin Plavnik of Sonotech, Inc.

Executive Summary

This report summarizes the findings of an evaluation of the pulse combustion burner system developed by Sonotech. The Cello® Pulse Burner system was demonstrated at the EPA IRF in Jefferson, AR, under the EPA SITE program. The Sonotech system was demonstrated in the autumn of 1994.

The purpose of this Innovative Technology Evaluation Report (ITER) is to present and summarize information from the SITE demonstration of the Sonotech system. The information is intended for remedial managers, environmental consultants, and other potential users who may consider using the technology to treat Superfund and RCRA hazardous wastes. Section 1.0 presents an overview of the SITE program, describes the Sonotech system, and lists key contacts. Section 2.0 discusses information relevant to the technology's application, including an assessment of the technology related to the nine feasibility study evaluation criteria, potential applicable environmental regulations, and operability and limitations of the technology. Section 3.0 summarizes the costs associated with implementing the technology. Section 4.0 presents the waste characteristics, demonstration approach, demonstration procedures, and the results and conclusions of the demonstration. Section 5.0 summarizes the technology status, and Section 6.0 includes a list of references. The Appendix presents case studies provided by the developer.

The remainder of this executive summary provides an overview of the Sonotech system; its waste applicability; demonstration objectives, approach, and conclusions; other case studies; and technology applicability.

The Sonotech System

Sonotech of Atlanta, GA, has developed a pulse combustion burner technology that claims to offer benefits when applied in a variety of combustion processes. The technology incorporates a combustor that can be tuned to induce large-amplitude acoustic or sonic pulsations inside combustion process units, such as boilers or incinerators.

A pulse combustor typically consists of an air inlet, a combustor section, and a tailpipe. In the Cello® system, fuel oxidation and heat release rates vary periodically with time, producing periodic variations or pulsations in pressure, temperature, and gas velocity. Sonotech claims that, when the entire unit is added to an existing incinerator, the large-amplitude resonant pulsations of acoustic or sound waves excited by its tunable pulse combustor can significantly improve an incinerator's performance, thereby reducing capital investment and operating costs for a wide variety of incineration systems.

To excite large-amplitude pulsations inside an incinerator, the pulse combustor must operate at a frequency that equals one of the natural, acoustic mode frequencies of the incinerator. When this condition is satisfied, the pulsations inside the pulse combustor and the incinerator are in resonance. Production of large-amplitude pulsations is achieved by (1) retrofitting a tunable pulse combustor to a wall of the incinerator and (2) varying its frequency until one of the natural acoustic modes of the incinerator is excited. The desired resonant operating condition is established by using one or more pressure transducers to monitor changes in the amplitude of pulsations inside the incinerator in response to changing the pulse combustor frequency. The desired operating condition is reached when the transducers indicate that the amplitude of pulsations inside the incinerator has been maximized.

Pulse combustion can also be applied to a variety of other combustion processes such as boilers, dryers, and calciners. In such applications, the pulse combustor can be used as the combustion process burner, supplying all of the heat input to the process, or it can be used only to excite pulsations in the combustion process. When used in such applications, the pulse combustor delivers only a fraction of the combustion process heat input (as little as 2%), while still exciting resonant pulsations in the process combustor. The remaining heat input is supplied by the conventional burner.

Waste Applicability

The Sonotech Cello® system can be incorporated into the construction of most new combustion devices or can be retrofitted to many existing systems. The Cello® system can be used to treat any material typically treated in a conventional incinerator.

For the SITE demonstration, the waste feed for all test runs consisted of a mixture of contaminated soil, sludge, and tar from two abandoned manufactured gas plant (MGP) Superfund sites. One component of the waste feed consisted of a combination of pulverized coal and contaminated coal-tar sludge from the Peoples Natural Gas Company (Peoples) Superfund site in Dubuque, IA. The other components of the waste feed material were obtained from an MGP site in the southeastern U.S. and consisted of contaminated soil borings and tar waste from an oil gasification process.

Sonotech believes their technology is ready to be used for the full-scale incineration of contaminated solids, liquids, sludges, and medical wastes.

Demonstration Objectives and Approach

The primary objective of the SITE program demonstration was to develop test data to evaluate the treatment efficiency of the Sonotech Cello® system compared to conventional combustion. Test data were evaluated to determine if the Sonotech system (1) increased incinerator capacity, (2) increased the destruction and removal efficiency (DRE) of principal organic hazardous constituents (POHC), (3) decreased flue gas carbon monoxide (CO) emissions, (4) decreased flue gas emissions of nitrogen oxides (NO_x), (5) decreased flue gas soot emissions, (6) decreased combustion air requirements, and (7) decreased auxiliary fuel requirements.

The demonstration's secondary objective was to develop additional data to evaluate whether the Sonotech system, compared to conventional combustion, (1) reduced the magnitude of transient puffs of CO and total unburned hydrocarbons (TUHC); (2) resulted in reduced incineration costs; (3) significantly changed the distribution of hazardous constituent trace metals among the incineration system discharge streams (including kiln bottom ash, scrubber liquor, and baghouse exit flue gas); and (4) increased the leachability of the toxicity characteristic leaching procedure (TCLP) trace metals from kiln ash.

The demonstration program objectives were achieved by collecting solid, liquid, and gas phase samples, as well as Sonotech and IRF pilot-scale rotary kiln incineration system (RKS) process operating data. To meet the objectives, data were collected for four different incineration system operating conditions, each performed in triplicate, for a total of 12 individual tests. The four test conditions included the following:

- Test Condition 1, conventional combustion at typical operating conditions
- Test Condition 2, conventional combustion at its maximum feedrate
- Test Condition 3, Sonotech pulse combustion at the maximum feedrate for conventional combustion (the same nominal feedrate as Test Condition 2)
- Test Condition 4, Sonotech pulse combustion at its maximum feedrate

Demonstration Conclusions

Data collected during the Sonotech SITE demonstration were evaluated using the rank sum test. The rank sum test allows the user to assess whether observed differences in data sets are statistically significant. When comparing two data sets, each containing three data points, the two data sets are different at the 95% confidence level when there is no data overlap. Unless noted, all conclusions are based on comparison of the average results from Test Condition 3 to the average results from Test Condition 2. The following conclusions may be drawn about the benefits of the Sonotech system:

- The Sonotech system increased the incinerator waste feedrate capacity by 13% compared to conventional combustion when comparing Test Condition 4 to Test Condition 2. The capacity increase was equivalent to reducing the auxiliary fuel needed to treat a unit mass of waste from an average of 21,100 British thermal units per pound of waste (Btu/lb) (range of 21,000 to 21,300) for conventional combustion to 18,000 Btu/lb (range of 16,600 to 19,000) for the Sonotech system. Visual observations indicated improved mixing in the incinerator cavity when the Sonotech system was operating.
- Benzene DREs for all 12 test runs were greater than 99.994%. The Sonotech system reduced the average benzene emission rate from 7.7 milligrams per hour (mg/hr) (range of 2.1 to 12) to 5.7 mg/hr (range of 3.4 to 6.9) at the afterburner exit.
- Naphthalene DREs were greater than or equal to 99.998% for all test runs. The Sonotech system reduced the average naphthalene emission rate from 1.2 mg/hr (range of less than 0.3 to 6.2) to 1.1 mg/hr (range of less than 0.3 to 2.5) at the afterburner exit.
- The average afterburner CO emissions, corrected to 7% oxygen (O_2), decreased from 20 parts per million (ppm) (range of 8.0 to 40.0) with conventional combustion to 14 ppm (range of 12.6 to 16.0) with the Sonotech system.
- The average afterburner NO_x emissions, corrected to 7% oxygen, decreased from 82 ppm (range of 78.3 to 85.1) with conventional combustion to 77 ppm (range of 68.0 to 87.1) with the Sonotech system.
- Average afterburner soot emissions, measured as total organic carbon (TOC) and corrected to 7% oxygen, were reduced from 1.9 milligrams per dry standard cubic meter (mg/dscm) (range of less than 0.9 to 2.7) for conventional combustion to less than 1.0 mg/dscm (range of less than 0.8 to 0.9) with the Sonotech system.
- Total system combustion air requirements, determined from stoichiometric calculations, were lower with the Sonotech system in operation. The ranges for these values were 38,400 to 40,600 dry standard cubic feet per hour (dscf/hr) without the Sonotech system and 34,800 to 39,900 dscf/hr with the Sonotech system operating.
- Total natural gas fuel requirements (including kiln and afterburner) for all test conditions were similar. The total system average natural gas usage was 1,540 dscf/hr (range of 1,480 to 1,590) for conventional combustion and 1,580 dscf/hr (range of 1,520 to 1,620) for the Sonotech system at approximately the same feedrate.

- No substantial increase or decrease occurred in the frequency or magnitude of transient CO or TUHC puffs with the Sonotech system operating.

- Under the demonstration test conditions, use of the Sonotech system with the reported increase in incineration capacity can result in a cost savings. The reader is referred to the Economics section of this report to determine the approximate cost savings for a specific application.

- During the Sonotech demonstration, the Cello® combustion system caused no downtime and was judged to be reliable.

- Target metals investigated included antimony, barium, beryllium, cadmium, chromium, lead, and mercury. Their distribution in the discharge streams of the RKS did not vary significantly from test to test or from test condition to test condition except for barium and chromium. Concentrations of these two metals were slightly lower in the scrubber liquor and measurably higher in the baghouse exit flue gas when the Sonotech system was operating.

- The concentrations of target metals in the TCLP leachates were low to not detected in the feed, kiln ash, and scrubber liquor. At these concentrations, no significant test-to-test variations in the TCLP leachability of the various discharge streams were observed.

- No volatile or semivolatile organic compounds, other than benzene, were detected in any kiln ash or scrubber liquor samples.

- Dioxin toxicity equivalent values for all runs were very low and no clear distinctions were noticed with the Sonotech system operating.

- Stack particulate and hydrogen chloride emissions were very low with no distinct variations between different test conditions.

Other Case Studies

According to the developer, the Sonotech system has been used, under test conditions, to evaluate the rate of spray evaporation of water, calcination of limestone, and heating of steel cylinders. Case studies, provided by Sonotech, involving these studies and the developer's interpretation of the data collected during this SITE demonstration, are included as Appendix A to this report.

Technology Applicability

Data obtained on the Sonotech system were analyzed to determine the advantages, disadvantages, and limitations of the technology. The Sonotech system was evaluated based on the nine criteria used for decision making in the Superfund feasibility study process.

For a given application, the overall effectiveness of the Sonotech system depends upon numerous factors including characteristics of the waste, such as its heat content, and the incinerator design, such as its waste feed system. The claimed benefits of the technology may only be fully realized with high heat-content, organic-contaminated soils.

The technology can be incorporated into almost any new incineration system and can be used as a retrofit to most existing incinerators, boilers, and dryers.

Materials-handling requirements and SITE-support requirements are minimal and are identical to those of the existing incinerator.

The SITE program demonstration evaluated the technology's ability to treat wastes contaminated with volatile and semivolatile organic compounds. Accordingly, the Sonotech system should be applicable to the incineration of wastes contaminated with pesticides, polychlorinated biphenyls (PCB), dioxins and furans.

Section 1.0
Introduction

This section provides background information about the EPA SITE program, discusses the purpose of this ITER, and describes the Cello® pulse burner system developed by Sonotech, of Atlanta, GA. Additional information about the SITE program, the Sonotech technology, and the demonstration can be obtained by contacting the key individuals listed at the end of this section.

1.1 The SITE Program

The SITE program was established by the EPA Office of Solid Waste and Emergency Response (OSWER) and Office of Research and Development (ORD) in response to the Superfund Amendments and Reauthorization Act of 1986 (SARA). The SITE program's primary purpose is to promote the use of alternative technologies in cleaning up hazardous waste sites. The various component programs under SITE are designed to encourage the development, demonstration, and use of new or innovative treatment and monitoring technologies. The program is designed to meet four primary objectives:

- Identify and remove obstacles to the development and commercial use of alternate technologies.
- Structure a development program that nurtures emerging technologies.
- Demonstrate promising innovative technologies to establish reliable performance and cost information for site characterization and cleanup decision-making.
- Develop procedures and policies that encourage the selection of available alternative treatment remedies at Superfund sites, as well as other waste sites and commercial facilities.

Technologies are selected for the SITE Demonstration Program through annual requests for proposals. ORD staff review the proposals to determine which technologies show the most promise for use at Superfund sites. Technologies chosen must be at the pilot- or full-scale stage, must be innovative, and must have some advantage over existing technologies. Mobile or transportable technologies are of particular interest.

Once EPA has accepted a proposal, cooperative agreements between EPA and the developer establish responsibilities for conducting the demonstrations and evaluating the technology. The developer is responsible for demonstrating the technology at the selected site and is expected to pay any costs of transporting, operating, and removing the equipment. EPA is responsible for project planning, sampling and analysis, quality assurance and quality control, preparing reports, disseminating information, and transporting and disposing of treated waste materials.

The results of the demonstration are published in two basic documents: the SITE Technology Capsule and the ITER. The SITE Technology Capsule provides preliminary information on the technology, emphasizing key results of the SITE demonstration. The ITER is discussed below. Both documents are intended for use by remedial managers who need a detailed evaluation of the technology for a specific site and waste.

1.2 Innovative Technology Evaluation Report

The ITER provides information on the Sonotech technology and includes a comprehensive description of the demonstration and its results. The ITER is intended for use by EPA remedial project managers, EPA on-scene coordinators, contractors, and other decision makers for implementing specific remedial actions. The ITER is designed to aid decision makers in further evaluating specific technologies for consideration as an applicable option in a particular cleanup operation.

To encourage the general use of demonstrated technologies, the ITER provides information regarding the applicability of each technology to specific sites and wastes. In particular, the report includes information on cost and site-specific characteristics. It also discusses advantages, disadvantages, and limitations of the technology.

Each SITE demonstration evaluates the performance of a technology in treating a specific material. Because the characteristics of other materials may differ from the characteristics of the treated material, successful field demonstration of a technology at one site does not necessarily ensure that it will be applicable at other sites. Data from the field demonstration may require extrapolation for estimating the operating ranges in which the technology will perform satisfactorily. Only limited conclusions can be drawn from a single field demonstration.

1.3 Project Description

Sonotech of Atlanta, GA, has developed a frequency-tunable pulse combustion burner technology that claims to offer benefits when applied in a variety of combustion processes. The burner system incorporates a pulse combustor that can be tuned to excite large-amplitude sonic pulsations inside a combustion chamber, such as a boiler or incinerator. These pulsations increase the rates of heat, mixing (momentum), and mass transfer in the combustion process. Sonotech claims that these rate increases in heat, mixing, and mass transfer are sufficient to result in significantly faster and more complete combustion.

Sonotech has targeted waste incineration as a potential application for this technology. In an earlier EPA demonstration of its pulse combustion system, Sonotech retrofitted a pulse combustion burner to the EPA bench-scale rotary kiln incinerator in Research Triangle Park, NC. Tests were performed to measure the effect of pulsations on incinerator emissions of soot, CO, and TUHC.

Based on this initial experience, Sonotech proposed a follow-up demonstration under the SITE program. Sonotech proposed that its pulse combustion technology be evaluated on a larger scale incineration system, specifically the pilot-scale RKS at the EPA IRF in Jefferson, AR.

To evaluate the Sonotech technology at the IRF, tests were performed in triplicate at four different incineration system operating conditions, for a total of 12 individual tests. The four test conditions included (1) conventional combustion at typical operating conditions; (2) conventional combustion at its maximum feedrate; (3) Sonotech pulse combustion at the conventional combustion maximum feedrate (the same nominal feedrate as condition 2); and (4) Sonotech pulse combustion at its maximum feedrate.

1.4 Technology Description

A pulse combustor typically consists of an air inlet, a combustor section, and a tailpipe. In pulse combustion, fuel oxidation and heat release rates vary over time. These variations produce periodic variations or pulsations in combustor section pressure, temperature, and gas velocities. The frequency of pulsations is generally close to the resonant frequency of the fundamental longitudinal acoustic mode of the combustor section and tailpipe. Thus, by changing combustor and tailpipe geometry—for example, by varying the length of the tailpipe—the frequency of pulsations can be changed, or tuned. Furthermore, if properly applied, a pulse combustor can excite large-amplitude resonant pulsations of 150 decibels (dB) or higher within a cavity downstream of the pulse combustor tailpipe. The combustion chamber of a boiler or an incinerator is an example of this type of cavity.

Compared to nonpulsating combustion, the technology's periodic pulsations in pressure, gas velocity, and temperature can increase the rates of mass, heat, and mixing transfer. Sonotech claims that these pulsations improve combustion efficiency and more completely oxidize or destroy organic compounds.

With the development of frequency-tunable pulse combustors that can excite large-amplitude pulsations in combustion chambers downstream of the pulse combustor, it becomes possible to apply pulse combustion to a variety of combustors, such as boilers, dryers, calciners, and incinerators. In such applications, the pulse combustor can be used as the main combustion burner, supplying all of the heat input to the process. Alternatively, the pulse combustor can be used only as the driver to excite pulsations in the combustion process. In such applications the pulse combustor would deliver only a fraction, as little as 2%, of the combustion heat input, while still exciting resonant pulsations in the combustor. The remaining heat input would be supplied by normal means, such as by the conventional burner.

To excite large-amplitude pulsations inside an incinerator, for example, the pulse combustor must operate at a frequency that equals one of the natural acoustic modes of the incinerator. When this condition is satisfied, the pulsations inside the pulse combustor and the incinerator are in resonance. Resonant driving of large-amplitude pulsations is achieved by retrofitting a tunable pulse combustor to a wall of the incinerator and varying its frequency until one of the natural acoustic modes of the incinerator is excited. The desired resonant operating condition is established in practice by using one or more pressure transducers to monitor changes in the amplitude of pulsations inside the incinerator in response to changes in the pulse combustor frequency. The desired operating condition is reached when these transducers indicate that the amplitude of pulsations inside the incinerator has been maximized.

The SITE demonstration of the Sonotech technology involved retrofitting the kiln section of the RKS at the IRF with a Sonotech pulse combustor to deliver a design heat input of 73 kilowatts (kW) (250,000 British thermal units per hour [Btu/hr]), or roughly 15% to 20% of the typical heat input to the kiln of the RKS. Sonotech claims that this application of the pulse combustion technology has the following advantages over conventional, nonpulsating incineration:

1. Higher incinerator capacity
2. Lower CO, soot, and NO_x emissions
3. Lower combustion air requirements
4. Lower energy requirements
5. Reduced severity of transient puffs
6. Reduced incineration system capital and operating costs

1.5 Key Contacts

Additional information on the Sonotech technology and the SITE program can be obtained from the following sources:

The Sonotech Technology

Dr. Ben T. Zinn
President
Sonotech, Inc.
3656 Paces Ferry Road
Atlanta, GA 30327
404-894-3033
FAX: 404-894-2760

The SITE Program

Robert A. Olexsey
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26 West Martin Luther King Drive
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26 West Martin Luther King Drive
Cincinnati, OH 45268
513-569-7692
FAX: 513-569-7676

Information on the SITE program is available through the following on-line information clearinghouses:

- The Alternative Treatment Technology Information Center (ATTIC) System is a comprehensive, automated, information retrieval system that integrates data on hazardous waste treatment technologies into a centralized source. The system operator can be reached at 301-670-6294.
- The Vendor Information System for Innovative Treatment Technologies (VISITT) database contains information on 154 technologies offered by 97 developers. The hotline number is 800-245-4505.
- The OSWER CLU-In electronic bulletin board contains information on the status of SITE technology demonstrations. The system operator can be reached at 301-585-8368.

Technical reports may be obtained by contacting the EPA Center for Environmental Research Information (CERI) at 26 West Martin Luther King Drive, Cincinnati, OH 45268; telephone 513-569-7562.

Section 2.0
Technology Applications Analysis

This section assesses the general applicability of the Sonotech Cello® pulse combustion system to remediate waste and contaminated soils from Superfund sites. This assessment is based on results from the demonstration of the technology under the EPA SITE Program.

The waste feed for all tests consisted of a mixture of contaminated materials from two abandoned MGP Superfund sites. One component of the test feed material was a combination of pulverized coal and contaminated coal-tar sludge from the Peoples Superfund site in Dubuque, IA. Other components of the test feed material included contaminated soil borings and a tar waste from an oil gasification process at an MGP site in the southeastern U.S.

2.1 Feasibility Study Evaluation Criteria

This subsection assesses the Sonotech technology relative to the nine evaluation criteria used to conduct detailed analyses of remedial alternatives in feasibility studies performed under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). Table 1 summarizes the evaluation criteria as they relate to the performance of the technology.

2.1.1 Overall Protection of Human Health and the Environment

This criterion addresses whether or not a remedy provides adequate protection and describes how risks posed by each pathway are eliminated, reduced, or controlled through treatment, engineering controls, or institutional controls.

The Sonotech technology provides both short- and long-term protection to human health and the environment by thermally destroying hazardous organic compounds contained in the wastes. Exposure from air emissions is minimized by removing contaminants in flue gas using an APCS. Potential accidental releases could temporarily affect air quality in the vicinity of the site. Short-term exposure to workers may occur when preparing the kiln ash and scrubber liquor for off-site disposal.

For the test program, the primary APCS consisted of a venturi scrubber followed by a packed-column scrubber and fabric-filter baghouse. The scrubber system was operated at as close to total recirculation (or zero blowdown) as possible. To assure permit compliance, a secondary, or redundant, APCS consisted of a demister, an activated-carbon adsorber and a high-efficiency particulate air (HEPA) filter.

2.1.2 Compliance with ARARs

This criterion addresses whether or not a remedy will meet all of the ARARs of other federal and state environmental statutes. General and specific ARARs identified for the Sonotech technology are presented in Section 2.2. Compliance with chemical-, location-, and action-specific ARARs should be determined on a site-specific basis; however, location-, and action-specific ARARs generally can be met. Compliance with chemical-specific ARARs depends on the chemical constituents of the waste and the treatment efficiency of the combustion system. A trial burn may be required to determine specific operating conditions.

2.1.3 Long-Term Effectiveness and Permanence

This criterion refers to the ability of a remedy to maintain reliable protection of human health and the environment over time.

Thermal destruction is a proven treatment technology for hazardous wastes containing organic compounds. The Sonotech system can be incorporated into the construction of most new combustion devices or can be retrofit to many existing systems to treat any material typically treated in a conventional incinerator. The Sonotech system was found to have a very small, but observable benefit, to the IRF RKS DRE of the POHC. POHC DREs measured for all test conditions were uniformly 99.994% or greater. Treatment residuals require proper off-site treatment and disposal.

2.1.4 Reduction of Toxicity, Mobility, or Volume through Treatment

This criterion refers to the anticipated performance of the treatment technology potentially used in a Superfund remediation. With incineration, the toxicity and volume of the waste feed is reduced through thermal destruction of hazardous organic components.

Sonotech test data demonstrated that organic components in the hazardous waste feed can be destroyed with at least 99.994% or greater DRE. The data also suggest that incineration residue quality, as measured by residue (kiln ash) heating value, was

Table 1. Feasibility Study Evaluation Criteria for the Sonotech Technology

Criterion	Sonotech Technology Performance
Overall Protection of Human Health and the Environment	The Sonotech technology used with a conventional combustion chamber destroys organic hazardous constituents in the waste feed. Air emissions are reduced by using an air pollution control system (APCS).
Compliance with Federal ARARs	Compliance with chemical-, location-, and action-specific applicable or relevant and appropriate requirements (ARARs) must be determined on a site-specific basis. Compliance with chemical-specific ARARs depends on the treatment efficiency of the combustion system and the chemical constituents of the waste.
Long-Term Effectiveness and Permanence	Contaminants are permanently removed from the waste. Treatment residuals from the APCS and the kiln ash require proper off-site treatment and disposal.
Reduction of Toxicity, Mobility, or Volume Through Treatment	With incineration, both the toxicity and volume of the waste are reduced by destroying organic components of the waste. Metals in the gas phase emissions and the kiln ash are unaffected.
Short-Term Effectiveness	The Sonotech system effectively reduces the time required for treatment by increasing the feedrate of a conventional combustion system. Short-term risks to workers, the community, and the environment arepresented during waste handling activities and from potential exposures to flue gas emissions and noise. Adverse impacts from both can be mitigated with proper controls and procedures.
Implementability	The Sonotech system can be easily incorporated into new incinerators and can be retrofit to most existing incinerators. In addition, the system can be used to treat any material treated in a conventional incinerator.
Cost	Under the demonstration test conditions,the Sonotech system can produce cost savings due to increased incinerator capacity. The reader is referred to Section 3.0 of this report, Economic Analysis, to determine the approximate cost saving for a particular application.
State Acceptance	State acceptance is anticipated to be favorable because the system can be retrofit to an existing permitted hazardous waste incinerator to improve the performance of conventional combustion technology.
Community Acceptance	The minimal short-term risks presented to the community along with the permanent removal of hazardous waste constituents and the improved performance of a permitted waste combustion unit should increase the likelihood of community acceptance of this technology.

improved with pulse combustion. The technology had no effect on the TCLP leachability of metals in kiln ash. Gas phase emissions were controlled by a primary and secondary APCS. Any treatment residual (such as kiln ash, scrubber liquor, or baghouse ash) possessing a hazardous waste characteristic must be shipped off site to a permitted treatment, storage, and disposal facility. No residuals from this demonstration possessed hazardous waste characteristics.

Sonotech demonstration test data showed that the concentrations of the target metals (antimony, barium, beryllium, cadmium, chromium, lead, and mercury) in the TCLP leachates were low or not detected in the feed, kiln ash, and scrubber liquor samples. At these concentrations, no significant variations in the TCLP leachability of the two waste streams were observed. Insufficient baghouse flyash was collected to allow for metals analysis of that waste.

2.1.5 Short-Term Effectiveness

This criterion addresses the period of time needed to achieve protection of human health and the environment and any adverse impacts that may be posed during the construction and implementation period until cleanup goals are achieved.

The Sonotech system can easily be incorporated into new incinerators or incineration systems and can be retrofit to most existing combustion systems. Installation of the Sonotech system to the IRF RKS and shakedown testing required about 2 weeks. Other than the noise produced by the system, no adverse impacts to the community, workers, or the environment would be anticipated as a result of the installation of the Sonotech system.

During the SITE demonstration, the capacity of the RKS incinerator (as judged by increased feedrate to the kiln) showed a 13% to 35% increase with the use of the Sonotech system over conventional combustion. The time requirement for treatment is effectively reduced by increasing the feedrate over a conventional combustion system.

Because the Sonotech system relies on the resonant frequency of the incinerator to excite large-amplitude pulsations, incorrect application of the sound energy generated by the pulse combustion may present structural problems in older incineration systems. Other noise problems caused by the system can be mitigated by enclosing the system with sound insulation and monitoring worker exposures to excessive noise levels. Other potential short-term risks presented during system operation to workers, the community, and the environment may include exposures to hazardous substances during waste handling activities and exposures to flue gas emissions. Adverse impacts during waste handling activities are minimized by following proper waste handling procedures and by using proper personal protection equipment (PPE). Adverse impacts from the flue gas emissions are mitigated by passing the emissions through an APCS.

2.1.6 Implementability

This criterion considers the technical and administrative feasibility of a remedy, including the availability of materials and services needed to implement a particular option.

The Sonotech system can be easily incorporated into new incinerators and can be retrofit to most existing incinerators. In addition, the system can be used to treat any material typically treated in a conventional incinerator with very few limitations.

Site requirements for an incinerator equipped with the Sonotech system would be nearly identical to those of an incinerator without the system. The Sonotech pulse combustor requires about 4 feet by 10 feet of additional area on one side of the incinerator where the system can be mounted. A port into the incinerator's primary combustion chamber is needed to insert the internal portion of the Sonotech burner. The system requires attachment of air and natural gas lines, and it requires only a nominal amount of additional electricity. Depending on the application and location, sound control may be necessary.

2.1.7 Costs

This criterion should address estimated capital and operation and maintenance costs as well as net present worth costs.

Under the demonstration test conditions, use of the Sonotech system can result in a cost savings due to increased incinerator capacity. The reader is referred to Section 3.0 of this report to determine the approximate cost savings for a particular application.

2.1.8 State Acceptance

This criterion addresses the technical or administrative issues and concerns the support agency may have regarding the technology.

State acceptance is anticipated to be favorable because the Sonotech system can be used as a retrofit to an existing permitted hazardous waste incinerator to improve the performance of the combustion technology. In cases where the installation of the pulse combustion technology increases the unit's feedrate, the Sonotech retrofit combustion unit would require a RCRA permit modification. The definition and requirements for a RCRA permit modification are provided in 40 Code of Federal Regulations (CFR) Part 270.42. The definition and requirements for a Clean Air Act (CAA) New Source Performance Standards (NSPS) modification are provided in 40 CFR Part 60.14. Generally, both modification processes require review by the permitting agency before retrofit. In addition, modification requirements may include public notification and retesting of the unit.

The Sonotech SITE demonstration was conducted under the restrictions of the IRF hazardous waste management permit, administered by the Arkansas Department of Pollution Control and Ecology. Test data indicate that the pulse combustion technology increased the waste feedrate without resulting increases in flue gas soot, CO, or NO_x emissions.

2.1.9 Community Acceptance

This criterion addresses any issues or concerns the public may have regarding the technology.

Public acceptance of this technology should be positive for three reasons: (1) the technology presents minimal short-term risks to the community, (2) it permanently removes hazardous constituents from the waste, and (3) it improves the performance of a permitted waste combustion unit.

2.2 Technology Performance Regarding ARARs

This section discusses potential environmental regulations pertinent to the demonstration and operation of the Sonotech pulse combustion system, including the transport and treatment, storage, and disposal (TSD) of wastes and treatment residuals. CERCLA, as amended by SARA, requires consideration of ARARs. CERCLA issues, although not true ARARs, are also considered.

Regulations that apply to a particular remediation activity depend on the type of remediation site and the type of waste treated. State and local regulatory requirements, which may be more stringent, must also be addressed by remedial managers. ARARs for the Sonotech demonstration or potential use of the Sonotech technology include the following: (1) RCRA, (2) CAA, (3) Toxic Substances Control Act (TSCA), and (4) Occupational Safety and Health Administration (OSHA) regulations. Table 2 summarizes these regulations, which are discussed in greater detail below.

2.2.1 Comprehensive Environmental Response, Compensation, and Liability Act

CERCLA, as amended by SARA, provides for federal authority to respond to releases or potential releases of any hazardous substance into the environment, as well as to releases of pollutants or contaminants that may present an imminent or significant danger to public health and welfare or the environment. Remedial alternatives that significantly reduce the volume, toxicity, or mobility of hazardous materials and provide long-term protection are preferred. Selected remedies must also be cost-effective and protective of human health and the environment.

Sonotech demonstration test data showed that the concentrations of the target metals (antimony, barium, beryllium, cadmium, chromium, lead, and mercury) in the TCLP leachates were low or not detected in the feed, kiln ash, and scrubber liquor samples. At these concentrations, no significant variations in the TCLP leachability of the two waste streams were observed.

The Sonotech system has demonstrated that it can destroy hazardous organic constituents in the feed stream with at least 99.99 DRE in the IRF RKS. Emissions of flue gases were controlled with primary and secondary APCSs.

Table 2. Potential Federal ARARs for the Sonotech Pulse Combustion System

Process Activity	ARAR	Description	Basis	Requirements
Waste feed characterization	RCRA 40 CFR Part 267 or state equivalent	Identify and characterize the waste to be treated	A RCRA requirement must be met before managing and handling the waste.	Chemical and physical analyses must be performed.
	TSCA 40 CFR Part 761 or state equivalent	If appropriate, apply standards to the treatment and disposal of wastes containing PCB	During waste characterization, PCBs may be identified in the waste feed and would then be subject to TSCA regulations	Chemical and physical analyses must be performed. If PCBs are identified, the waste feed will be managed according to TSCA regulations.
Transportation for off-site treatment	RCRA 40 CFR Part 262 or state equivalent	Mandate manifest requirement, packaging, and labeling prior to transporting	The waste may need to be manifested and managed as hazardous waste.	An identification number must be obtained from EPA.
	RCRA 40 CFR Part 261 or state equivalent	Set transportation standards	The waste may need permits for transportation as a hazardous waste.	A transporter licensed by EPA must be used to transport the hazardous waste.
Storage prior to processing	RCRA 40 CFR Part 264 or state equivalent	Apply standards for the storage of hazardous waste	Prior to treatment, the hazardous waste may require on-site storage in a waste pile, tank, or container.	The material should be placed in a waste pile on plastic and covered with additional plastic that is secured to minimize fugitive air emissions and volatilization. Tanks or containers must be well maintained; the container storage area, if used, must be constructed to control runon and runoff. The time between storage and treatment should be minimized.
Waste processing - incineration	RCRA 40 CFR Parts 264, 265, 266 (Boilers and Industrial Furnaces [BIF] Rule in Subpart H), and 270	Apply standards for the incineration of hazardous waste at permitted and interim status facilities	Incineration of hazardous waste must be conducted in a manner that meets the RCRA operating and monitoring requirements.	Equipment must be operated and maintained daily. Air emissions must be characterized by continuous emissions monitoring (CEM). Equipment must be decontaminated when operations are complete.
	TSCA 40 CFR Part 761.70	Apply performance standards for the incineration of liquid and nonliquid PCB waste	Incineration of PCB wastes must be conducted in a manner that meets the TSCA operating and monitoring requirements.	Rate and quantity of feed stream must be measured and recorded at regular intervals; temperature of incinerator shall be continuously measured and recorded; temperature-specific residence time requirements must be met.
Storage after processing	RCRA 40 CFR Part 264 or state equivalent	Apply standards for the storage of hazardous waste: requirements for storage of hazardous waste in tanks and containers will apply	If treatment residue is derived from the treatment of a RCRA hazardous waste, requirements for storage of hazardous waste in tanks and containers will apply.	The treatment residue must be stored in tanks or containers that are well maintained; container storage area, if used, must be constructed to control runon and runoff.
On- or off-site disposal	RCRA 40 CFR Part 264 or state equivalent	Apply standards for landfilling hazardous waste	Treatment residue may need to be managed as a hazardous waste if it is derived from treatment of hazardous waste.	Wastes must be disposed of at a RCRA-permitted hazardous waste facility, or approval must be obtained from EPA to dispose of wastes on site.

(continued)

Table 2. Continued

Process Activity	ARAR	Description	Basis	Requirements
	RCRA 40 CFR Part 268 or state equivalent	Apply standards that restrict the placement of certain hazardous wastes in or on the ground	The hazardous waste may be subject to federal land disposal restrictions (LDR).	Wastes must be characterized to determine if LDRs apply; treated wastes must be tested and results compared to standard.
Transportation for off-site processing	RCRA 40 CFR Part 262 or state equivalent	Apply manifest requirements and packaging and labeling requirements prior to transporting	The treatment residue may need to be manifested and managed as a hazardous waste if it is derived from treatment of hazardous waste.	An identification number must be obtained from EPA
	RCRA 40 CFR Part 263 or state equivalent	Apply transportation standards	Spent carbon may need to be transported as a hazardous waste if it is derived from treatment of hazardous waste.	A transporter licensed by EPA must be used to transport the hazardous waste according to EPA regulations.
Flue Gas Emissions	CAA or equivalent State Implementation Plan	Control air emissions that may impact attainment of ambient air quality standards	The Sonotech technology system can incorporate a primary and secondary APCS to treat flue gas emissions. Treated air is emitted to the atmosphere.	Treatment of contaminated air must adequately remove contaminants so that air quality is not impacted.
Worker Safety	OSHA 29 CFR Parts 1900 through 1926; or state OSHA requirements	Apply worker health and safety standards	CERCLA Remedial actions and RCRA corrective actions must follow requirements for the health and safety of on-site workers.	Workers must have completed and maintained OSHA training and medical monitoring; use of appropriate personal protective equipment (PPE) is required.

Incineration of hazardous waste generally takes place off site at a RCRA-permitted TSD facility, although portable incinerators can be used for on-site treatment. The Sonotech system can be applied to either of these applications. Disposal of residual wastes generated during on-site application might require off-site disposal or treatment. All on-site actions must meet all substantive state and federal ARARs. Substantive requirements pertain directly to actions or conditions in the environment (e.g., air emission standards). Off-site actions must comply with legally applicable substantive and administrative requirements; administrative requirements, such as permitting, facilitate the implementation of substantive requirements.

On-site remedial actions must comply with all federal ARARs as well as more stringent state ARARs. ARARs are determined on a site-by-site basis and may be waived under six conditions: (1) the action is an interim measure, and the ARAR will be met at completion; (2) compliance with the ARAR would pose a greater risk to health and the environment than noncompliance; (3) it is technically impracticable to meet the ARAR; (4) the standard of performance of an ARAR can be met by an equivalent method; (5) a state ARAR has not been consistently applied elsewhere; and (6) fund balancing, where ARAR compliance would entail such cost in relation to the added degree of protection or reduction of risk afforded by that ARAR that remedial action at other sites would be jeopardized. These waiver options apply only to Superfund actions taken on site, and justification for the waiver must be clearly demonstrated. Off-site remediations are not eligible for ARAR waivers, and all substantive and administrative applicable requirements must be met.

2.2.2 Resource Conservation and Recovery Act

RCRA, as amended by the Hazardous and Solid Waste Disposal Amendments of 1984, regulates the management and disposal of municipal and industrial solid wastes. The EPA and RCRA-authorized states [listed in 40 CFR Part 272] implement and enforce RCRA and state regulations.

A retrofit application of the Sonotech pulse combustion system with a rotary kiln incinerator was evaluated by using a hazardous waste feed mixture of sludge, soil, tar, and coal. The Sonotech system may also be used with other combustion process units, such as BIF, to treat a variety of waste types. The pertinent RCRA regulations would need to be determined for each specific application.

The presence of RCRA-defined hazardous waste determines whether RCRA regulations apply to the Sonotech technology. If hazardous wastes are treated or generated during the operation of the technology, all RCRA requirements regarding the management and disposal of hazardous wastes must be addressed. RCRA regulations define hazardous wastes and regulate their transport and TSD. Wastes defined as hazardous under RCRA include characteristic and listed wastes. Criteria for identifying characteristic hazardous wastes are included in 40 CFR Part 261 Subpart C. Listed wastes from nonspecific and specific industrial sources, off-specification products, spill cleanups, and other industrial sources are itemized in 40 CFR Part 261 Subpart D.

If hazardous wastes are treated by the Sonotech system, the owner or operator of the treatment or disposal facility must obtain an EPA identification number and a RCRA permit from EPA or the RCRA-authorized state. RCRA requirements for permits are specified in 40 CFR Part 270.

As mentioned in Section 2.1.8, in cases where the Sonotech system is retrofit to a permitted combustion unit and it increases the unit's overall feedrate, the modified unit will need to obtain a RCRA permit modification. The definition and requirements for a permit modification are provided in 40 CFR Part 270.42. Generally, the process requires a review by the permitting agency before beginning retrofit. In addition, modification requirements may include public notification and retesting of the unit.

In addition to the permitting requirements, owners and operators of incinerators that treat hazardous waste must comply with 40 CFR Part 264 Subpart O. If the Sonotech system is used to burn or process wastes in a BIF (as defined in 40 CFR Part 260.10), the BIF rule outlined in 40 CFR Part 266 Subpart H becomes an ARAR.

Treatment residuals generated during the operation of the system, including kiln ash, spent granular activated carbon, baghouse ash, and scrubber liquor, must be stored and disposed of properly. If the treatment waste feed is a listed waste, treatment residues must be considered listed wastes (unless RCRA delisting requirements are met). If the treatment residues are not listed wastes, they should be tested to determine if they are RCRA characteristic hazardous wastes. If the residuals are not hazardous and do not contain free liquids, they can be disposed of on site or at a nonhazardous waste landfill. If the treatment residues are hazardous, the following RCRA standards apply:

- Standards and requirements for generators of hazardous waste, including hazardous treatment residues, are outlined in 40 CFR Part 262. These requirements include obtaining an EPA identification number, meeting waste accumulation standards, labeling wastes, and keeping appropriate records. Part 262 allows generators to store wastes up to 90 days without a permit and without having interim status as a TSD facility. If treatment residues are stored on site for 90 days or more, 40 CFR Part 265 requirements apply.
- Any on- or off-site facility designated for permanent disposal of hazardous treatment residues must be in compliance with RCRA. Disposal facilities must fulfill permitting, storage, maintenance, and closure requirements provided in 40 CFR Parts 264 through 270. In addition, any authorized state RCRA requirements must be fulfilled. If treatment residues are disposed of off-site, 40 CFR Part 263 transportation standards apply.

The waste feed mixture used during the Sonotech demonstration included contaminated soil borings from an MGP Superfund site. Soils classified as hazardous waste are subject to land disposal restrictions (LDR) under both RCRA and CERCLA. Applicable RCRA requirements may include (1) a Uniform Hazardous Waste Manifest if the treated soils are transported, (2) restrictions on placing soils in land disposal units, (3) time limits on accumulating treated soils, and (4) permits for storing treated soils.

Requirements for corrective action at RCRA-regulated facilities are provided in 40 CFR Part 264, Subpart F (promulgated) and Subpart S (proposed). These subparts also apply to remediation at Superfund sites. Subparts F and S include requirements for initiating and conducting RCRA corrective actions, remediating groundwater, and ensuring that corrective actions comply with other environmental regulations. Subpart S also details conditions under which particular RCRA requirements may be waived for temporary treatment units operating at corrective action sites. Thus, RCRA mandates requirements similar to CERCLA, and as proposed, may allow treatment units such as the Sonotech treatment system to operate without full permits.

2.2.3 Clean Air Act

The CAA and its 1990 amendments establish primary and secondary ambient air quality standards for protection of public health and emission limitations on certain hazardous air pollutants.

CAA permitting requirements are administered by each state as part of State Implementation Plans developed to bring each state into compliance with National Ambient Air Quality Standards (NAAQS). Ambient air quality standards for specific pollutants apply to the operation of the Sonotech system, because the technology ultimately results in an emission from a point source to the ambient air. Allowable emission limits for the operation of a Sonotech system will be established on a case-by-case basis depending upon the type of waste treated and whether or not the site is in an attainment area of the NAAQS. Allowable emission limits may be set for specific hazardous air pollutants, particulate matter, hydrogen chloride, or other pollutants. If the site is in an attainment area, the allowable emission limits may still be curtailed by the increments available under Prevention of Significant Deterioration (PSD) regulations. Typically, an APCS similar to the type used during the SITE demonstration will be required to control the discharge of flue gas emissions to the ambient air.

ARARs pertaining to the CAA must be determined on a site-by-site basis. Remedial activities involving the Sonotech technology may be subject to the requirements of Title I of the CAA for the PSD of air quality in attainment (or unclassified) areas. The PSD requirements will apply when remedial activities involve a major source or modification as defined in 40 CFR Section 52.21; remedial activities subject to review must apply the best available control technologies and demonstrate that the activity will not adversely impact ambient air quality.

2.2.4 Toxic Substances Control Act

The disposal of PCB is regulated under Section 6(e) of TSCA. PCB treatment and disposal regulations are described in 40 CFR Part 761. Materials containing PCBs in concentrations between 50 and 500 ppm may either be sent to TSCA-permitted landfills or destroyed by incineration at a TSCA-approved incinerator. At concentrations greater than 500 ppm, the material must be incinerated. Sites where PCB spills have occurred after May 4, 1987, must be addressed under the PCB Spill Cleanup Policy outlined in 40 CFR Part 761, Subpart G. The policy applies to spills of materials containing 50 ppm or greater of PCBs and establishes cleanup protocols for addressing such releases, based on the volume and concentration of spilled material.

Application of the Sonotech system to an incinerator may be an effective thermal destruction system for treating solid and liquid wastes containing PCBs. If the system is used to treat PCB-contaminated material, the remediation will require TSCA authorization that defines operational, throughput, and disposal constraints. If the PCB-contaminated material contains RCRA wastes, RCRA compliance is also required.

2.2.5 Occupational Safety and Health Administration Requirements

CERCLA remedial actions and RCRA corrective actions must be performed in accordance with OSHA requirements detailed in 20 CFR Parts 1900 through 1926, especially Part 1910.120, which provides for the health and safety of workers at hazardous waste sites. On-site construction activities, such as assembly of a transportable incinerator, at Superfund or RCRA corrective actions sites must be performed in accordance with Part 1926 of OSHA, which provides safety and health regulations for construction sites. State OSHA requirements, which may be significantly stricter than federal standards, must also be met.

All technicians operating the Sonotech treatment system are required to have completed an OSHA training course and must be familiar with all OSHA requirements relevant to hazardous waste sites. For most sites, minimum PPE for technicians will include gloves, hard hats, steel-toe boots, and coveralls. Depending on contaminant types and concentrations, additional PPE may be required.

The Sonotech system produces a considerable volume of noise. This noise can be controlled to a degree by sound insulation, placement of the pulse combustor, or other means. Noise levels will need to be monitored to ensure that workers are not exposed to noise levels above a time-weighted average of 85 dBs over an 8-hour day.

2.2.6 Technology Performance Regarding ARARs During the Demonstration

In general, operation of the Sonotech Cello® combustor retrofit to the IRF RKS met all applicable requirements of the ARARs listed in Table 2. The specifics of the technology performance versus the ARARs are discussed below.

Waste characterization and feed preparation requirements would be the same for both conventional incineration (without the pulse combustor retrofit), and with the Sonotech pulse combustor retrofit. Typically, solid waste incineration in a rotary kiln incinerator results in two residual discharge streams -- solid kiln bottom ash and scrubber liquor. When these waste streams are derived from hazardous waste, they are treated as hazardous waste as in the case of this test program. Analysis of the scrubber liquor and kiln ash samples showed that, with respect to disposal, there was no difference in the quality of the product streams (scrubber liquor and kiln ash) between conventional incineration and the Sonotech system retrofit incineration. Therefore, application of Sonotech technology did not result in special requirements for the disposal of these waste streams.

Test results showed that flue gas emission performance specifications were met for both conventional incineration and Sonotech pulse combustion incineration. No special air pollution control device (APCD) was required, nor was there a need to operate any APCD at conditions different from conventional operation with the Sonotech system. The following are a summary of routine (permit-based) operating standards and performance specifications compliance requirements that were met, both under conventional incinerator operation and with the Sonotech system retrofit.

- Target POHCs (benzene and naphthalene) DREs were greater than 99.99% for all tests, as required by the hazardous waste incinerator performance standards, which would be ARARs for incineration treatment.

- Stack CO emissions were well below the permitted 100-ppm, 1-hour rolling average for all tests; this has become a permit requirement for permitted hazardous waste incinerators.

- Stack particulate loadings for all tests, at about 1 mg/dscm (0.0004 grains per dry standard cubic foot [grain/dscf]), were well below the maximum permissible level of 180 mg/dscm (0.08 grain/dscf) required by the hazardous waste incinerator performance standards, and even below the 1993 EPA guidance level for waste combustors of 34 mg/dscm (0.015 grain/dscf).

- Hydrogen chloride emissions for all tests were below 0.2 grams per hour (g/hr) (0.0004 pound per hour [lb/hr]), and well below the maximum permissible level of 1.8 kilograms per hour (kg/hr) (4 lb/hr) required by the hazardous waste incinerator performance standards.

- Dioxin and furan (PCDD and PCDF) emissions were at 0.1 nanograms per dry standard cubic meter (ng/dscm) or less, corrected to 7% oxygen. This is well below the 1993 EPA guidance of 30 ng/dscm corrected to 7% oxygen. On a 2,3,7,8-TCDD toxicity equivalents basis, the emissions were in the range of 0.0003 to 0.005 ng/dscm, corrected to 7% oxygen. This is considerably less than the recently proposed EPA standard of 0.2 ng/dscm, corrected to 7% oxygen.

In summary, operation of the Sonotech system during the demonstration test program was in compliance with the RCRA-based ARARs that would apply to an incineration process at a Superfund site.

One potential issue affecting worker health and safety was the noise-level of about 100 dB that was generated within the vicinity of the Sonotech pulse combustor during its operation. OSHA guidelines limit an individual's daily maximum exposure to noise-levels of no greater than 85 dB on an 8-hour average basis. During this test program IRF personnel were required to wear suitable hearing protection devices when working near the Sonotech system.

2.3 Operability of the Technology

The Sonotech Cello® pulse combustor was attached to the primary combustion chamber of the RKS, as shown in Figure 1. A previously existing hatch was removed and a flanged plate was fabricated to attach the pulse combustor to the kiln. Natural gas and air lines were drawn from the existing gas and air trains for the IRF RKS. The efforts involved in configuring the Sonotech pulse combustor into the RKS were moderate. After an initial training totaling about 3-4 hours, the IRF operations crew were able to easily operate the Sonotech burner. Startup and operation of the Sonotech burner required manually turning on the gas and air valves, setting them to the desired flowrates, turning on the pulse combustion burner, allowing the burner to heat up for 10-15 minutes after ignition, connecting the burner to the kiln chamber, and then adjusting the pulsation frequency to achieve resonance. This entire sequence of events took about 20-30 minutes. The Sonotech burner operating conditions and system maintenance requirements are further discussed in Sections 4.3.1.1 and 4.3.1.2.

2.4 Applicable Wastes

The Sonotech combustor can be incorporated into the construction of most new combustion devices or can be retrofit to many existing systems. The burner system can be used to treat any material typically treated in a conventional combustion device, and Sonotech believes the technology is ready to be used for the full-scale incineration of contaminated solids, liquids, sludges, and medical wastes. Coal and contaminated soil, sludge, and tar samples collected from two Superfund sites were blended for use in this SITE demonstration.

2.5 Key Features of the Sonotech Cello® Pulse Combustion System

The Sonotech Cello® pulse combustion system typically consists of an air inlet, a combustor section, and a tailpipe. In the Sonotech pulse combustor, fuel oxidation and heat release rates vary periodically with time, producing periodic variations or pulsations in pressure, temperature, and gas velocity (see Figure 2). Sonotech claims that large-amplitude resonant pulsations excited by its frequency-tunable pulse combustor can significantly improve an incinerator's performance, thereby reducing capital investment and operating costs for a wide variety of incineration systems.

2.6 Availability and Transportability of Equipment

The Cello® pulse combustion system is available from Sonotech, Inc., of Atlanta, GA (see Section 1.5 for address and telephone number). The system can be designed as a retrofit to existing incinerators or can be designed as an integral component of a new incinerator. For most applications, the Sonotech system can be transported in a medium-duty truck.

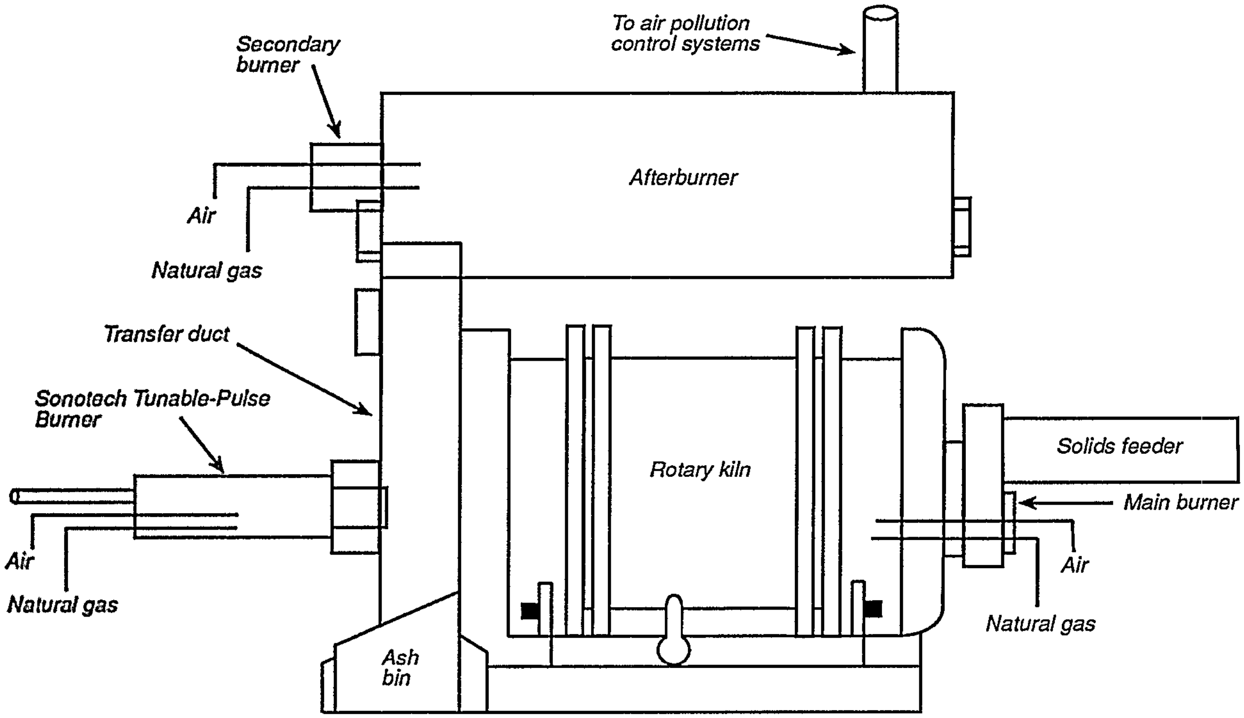


Figure 1. Sonotech Cello® Pulse Combustion Burner System fitted to the IRF RKS.

2.7 Materials-Handling Requirements

Materials-handling requirements for an incinerator are not affected by using the Sonotech system; however, the Sonotech system may result in an increased feedrate to the incinerator.

2.8 Site-Support Requirements

Use of the Sonotech unit requires natural gas, fuel oil, or another energy source; an air or oxygen source; and an electrical connection. The amounts of these three consumable requirements are comparable to those needed for a similar sized burner.

The Sonotech system generates noise in the 100-dB range. In a typical work environment, noise levels may be high enough to cause concern. Sonotech can enclose the system in sound-insulating material to reduce the noise intensity, or the entire incinerator may be enclosed to reduce the noise.

2.9 Limitations of the Technology

The Sonotech Cello® pulse combustion system has the same limitations as a nonpulsating burner attached to a combustion device. As mentioned above, the system produces considerable noise, which may be controlled by sound insulation.

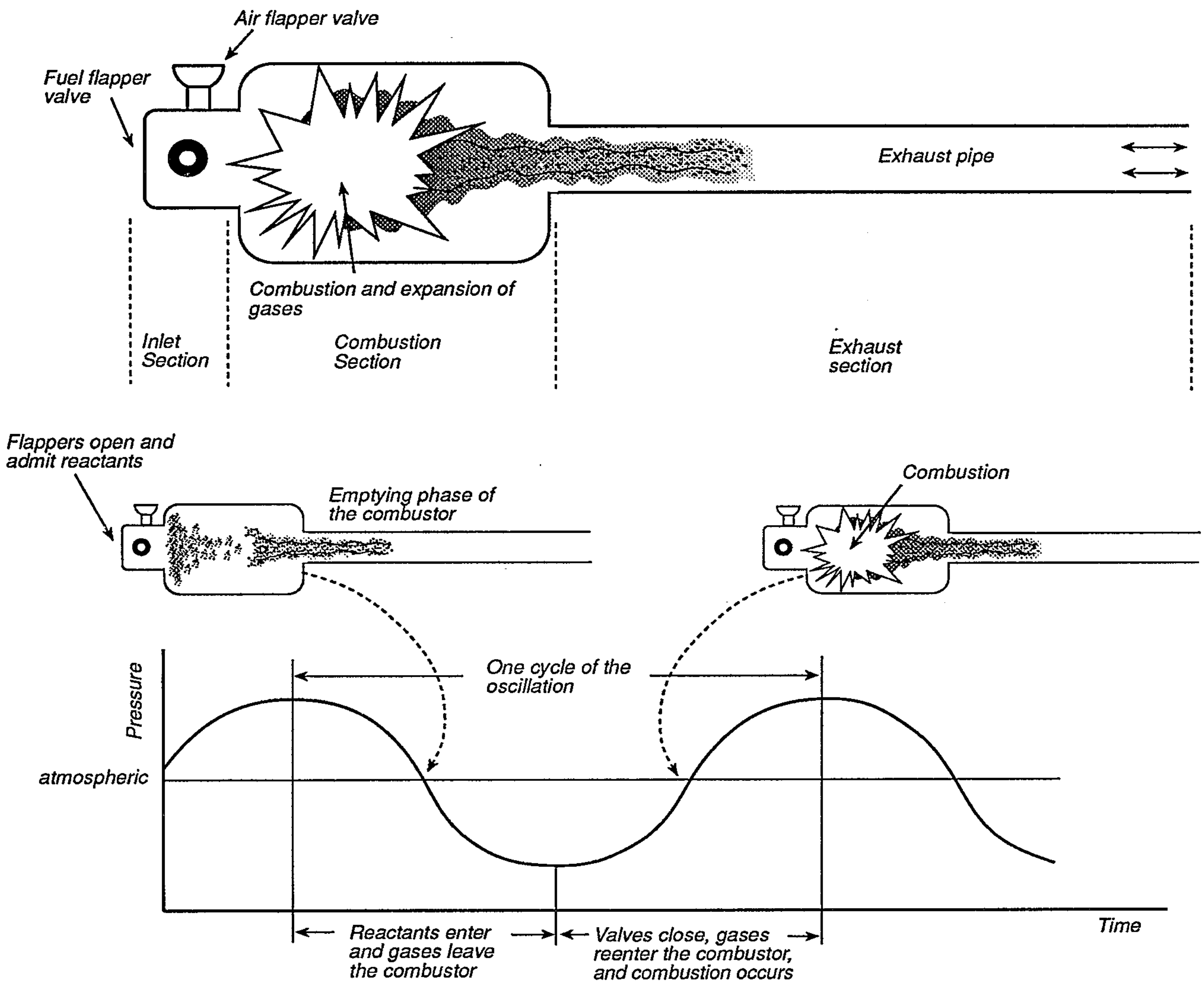


Figure 2. Key features of the Sonotech Cello® Pulse Combustion System.

Section 3.0
Economic Analysis

3.1 Introduction

This economic analysis presents a cost estimate for installing and operating the Sonotech Cello® pulse combustion burner. Cost data were compiled during a SITE technology demonstration at the EPA IRF in Jefferson, AR, and from information obtained from the technology developer. Costs have been estimated for 12 categories applicable to typical cleanup activities at Superfund and RCRA sites (Evans 1990). Costs are presented in March 1995 dollars and are considered to be order-of-magnitude estimates with an expected accuracy between 50% above and 30% below the actual costs.

This section discusses issues and assumptions used to define a typical-use scenario for this technology, the analysis of each of the 12 cost categories, and conclusions of this analysis.

3.2 Issues and Assumptions

This section summarizes the major issues and assumptions used in the economic analysis of the Sonotech technology. Issues and some assumptions are presented in text; major assumptions are presented as bullets at the end of Sections 3.2.1 and 3.2.2. In general, pulse combustion burner operating issues and assumptions are based on information obtained from and observations made during the Sonotech SITE demonstration. Certain assumptions were made to account for variable incinerator parameters; others were made to simplify cost estimating for situations that would actually require complex engineering or financial functions.

3.2.1 Equipment and Operating Parameters

The Sonotech system can be used in a variety of combustion processes. The system incorporates a combustor that can be tuned to induce large-amplitude sonic pulsations inside combustion process units such as boilers or incinerators. These pulsations increase heat release, mixing, and mass transfer rates in the combustion process, resulting in faster and more complete combustion. The SITE demonstration showed that the pulse combustion burner system increased the feedrate of a pilot-scale incinerator by 13% to 35%. It is assumed that this same feedrate increase will be observed on a full-scale incinerator. The system can be used to treat any material typically treated in a conventional incinerator, including soils, sludges, medical wastes, and liquids contaminated with volatile organic compounds (VOC) or semivolatile organic compounds (SVOC).

Sonotech will configure the pulse combustion burner system to accommodate the operating parameters of a customer's existing incinerator. Because the operating parameters and costs for an incinerator can vary greatly depending on the incinerator type, energy used, media to be treated, and regulatory requirements, determining the exact costs associated with the application of the Sonotech system can be difficult. To assist the decision maker, a worksheet has been provided in Section 3.4, Conclusions of Economic Analysis, to allow the operator of an existing incinerator to compare current operating costs with the operating costs of the incinerator retrofit with the Sonotech system.

Equipment and operating parameter assumptions include the following:

- The pulse combustion burner equipment is retrofit to an existing incinerator by Sonotech personnel.
- The Sonotech system is configured for an incinerator that has a feedrate of 2 tons per hour and operates at 30 million Btu/hr.
- The Sonotech system increases the waste feedrate by 15% above the normal feedrate, observed at the Sonotech SITE demonstration.
- The Sonotech system is operated 24 hours per day, 7 days per week, with an on-line operating efficiency of 80%; therefore, real operating time is 42 weeks per year.
- The Sonotech system operates automatically, requiring no additional labor efforts.
- No additional air emission monitoring is necessary. The system uses existing incinerator monitoring equipment and does not generate emissions requiring additional monitoring equipment.
- Very minimal additional space is needed to house the technology.

3.2.2 Additional Assumptions

The following additional assumptions were used in this economic analysis:

- The existing incinerator is located 500 miles from the Sonotech facility, requiring that the Cello® pulse combustion burner be transported 500 miles.
- The medium to be treated consists of soil contaminated with naphthalene at 10,000 milligrams per kilogram (mg/kg) and benzene at 30,000 mg/kg, which is similar to the type and concentration of contaminants in the SITE demonstration soil.
- The Sonotech system meets treatment goals for the soil.
- All costs are rounded to the nearest $100.

3.2.3 Financial Calculations

When estimating costs for a capital investment, depreciation should be considered. Depreciation measures the value of the physical capital a firm uses in its production as that capital is "used up." Because depreciation of capital costs can be claimed as a tax deduction, it provides a means for a firm to recover some of its capital cost. For this analysis, a straight-line depreciation method was used. This method assumes that the value of the capital is deducted in equal installments over the 3-year life of the equipment. For further discussion of the depreciation associated with the Sonotech system, see Section 3.3.4, Equipment Costs.

3.3 Cost Categories

Cost data associated with the Sonotech technology has been assigned to the following 12 cost categories: (1) site preparation, (2) permitting and regulatory costs, (3) mobilization and start-up, (4) equipment, (5) labor, (6) supplies, (7) utilities, (8) effluent treatment and disposal, (9) residual waste shipping and handling, (10) analytical services, (11) equipment maintenance, and (12) demobilization. Each of these cost categories is discussed below. Table 3 presents a breakdown of the costs assigned to each of the 12 categories.

3.3.1 Site Preparation Costs

Site preparation costs include administration, treatment area preparation, and treatability study costs. For this analysis, site preparation costs are $0 because the Sonotech system is mounted to an existing incinerator, and no additional construction costs are incurred.

3.3.2 Permitting and Regulatory Costs

Permitting and regulatory costs are incurred for the operation of an incinerator. This analysis assumes that for an existing RCRA incinerator, required permitting and regulatory costs have already been incurred. However, according to 40 CFR Part 270.42, the addition of the Sonotech system to an existing RCRA incinerator would be classified as a Class 2 permit modification. As a result, about 24 hours would be spent addressing the regulatory requirements associated with such a modification. Therefore, at a fully loaded labor rate of $40 per hour, the total permitting and regulatory costs are estimated to be $1,000.

3.3.3 Mobilization and Start-Up Costs

Mobilization and start-up costs include the costs of transporting the Cello® pulse combustion burner equipment to the incinerator, assembling the system, and performing the initial shakedown of the system. Sonotech provides trained personnel to assemble and shake down the treatment system; these personnel are assumed to be trained in hazardous waste site health and safety procedures. Initial operator training is needed to ensure safe, economical, and efficient operation of the system. Sonotech provides up to 40 hours of initial operator training to its clients at no additional cost.

However, the client will incur the labor costs associated with the trainees attending a 40-hour-course. This analysis assumes that two operators per shift plus an additional backup person will receive the training. This will result in a total of 9 people attending the training course. Assuming that the employees earn a fully loaded rate of $35 per hour, the client will incur a cost of $12,600 as a result of training its employees to operate the Sonotech system.

Transportation costs vary depending on the location of the existing incinerator in relation to the Sonotech facility. For this analysis, the equipment is assumed to be transported 500 miles. Sonotech typically retains the services of a cartage company to transport all pulse combustion burner equipment. Based on these parameters, cartage companies currently charge $1.00 per mile,

Table 3. Costs Associated with the Sonotech Technology

Cost Category	Expenses[a]
Site Preparation	$0
Permitting and Regulatory Costs	1,000
Mobilization and Start-Up	13,100
Equipment[b]	36,000
Labor	0
Supplies	0
Utilities	0
Effluent Treatment and Disposal	0
Residual Waste Shipping and Handling	0
Analytical Services	0
Equipment Maintenance	3,800
Demobilization	0
Total Costs for the Useful Life of the Equipment	$53,900
Average Annual Operating Costs	$18,000

[a]Costs are in March 1995 dollars.

[b]After depreciation.

for a total cost of $500. Because the system is not very heavy, it could be picked up and transported in a standard pickup truck.

3.3.4 Equipment Costs

Equipment costs consist of the purchase cost of the Cello® pulse combustion burner system. For this analysis, Sonotech estimates a base cost of $60,000 for the capital equipment needed for a system configured for a 30-million Btu/hr incinerator. The equipment has an estimated operational life of 3 to 5 years and no salvage value. After adjusting equipment costs for depreciation, the effective cost of the system is $36,000. Table 4 details the corporate income tax savings resulting from equipment depreciation over 3 years.

3.3.5 Labor Costs

Once the Sonotech system is functioning, it is assumed to operate continuously at the designed feedrate, except during routine maintenance conducted by Sonotech over the life of the equipment (see Section 3.3.11, Equipment Maintenance Costs). No labor costs are incurred beyond those necessary to operate the existing incinerator.

3.3.6 Supply Costs

The Sonotech system operates continuously using a combustor that can be tuned to induce large amplitude sonic pulsations inside combustion process units. Therefore, no direct supply costs are expected to be incurred beyond those necessary to operate the existing incinerator.

3.3.7 Utility Costs

The energy requirements of the Sonotech system are less than 5,000 kilowatt hours (kWh) per year. In addition, the improved heat transfer produced by the system may increase the rate of drying and heating the waste, which in turn would increase the burn rate and reduce the total fuel consumption of an incinerator. Actual energy consumption will vary among incinerators and therefore is difficult to estimate for this analysis. However, because the relative change in costs is assumed to be negligible, this analysis assumes no additional utility costs.

3.3.8 Effluent Treatment and Disposal Costs

No costs are incurred for effluent treatment and disposal, because the Sonotech system does not produce an effluent.

Table 4. Equipment Depreciation

Year	Depreciation Deduction for Tax Purposes	Income Tax Savings at Corporate Rate of 40%
1	$20,000	$8,000
2	$20,000	$8,000
3	$20,000	$8,000

3.3.9 Residual Waste Shipping and Handling Costs

The Sonotech system increases an existing incinerator's feedrate, which in turn increases the volume of incinerator ash requiring disposal. However, for this analysis, this increased volume will not be attributed to the Sonotech system. As a result, no additional costs for residual waste shipping and handling are incurred, because the same quantity of incinerator ash is produced by a conventional incinerator as by the same incinerator equipped with the Sonotech system.

3.3.10 Analytical Service Costs

Sampling frequency and sample quantities are incinerator-specific and are based on regulatory agency requirements. Sampling and analytical costs are typically associated with operating an incinerator; however, no additional sampling and analytical costs would be incurred by operating an incinerator equipped with the pulse combustion burner.

3.3.11 Equipment Maintenance Costs

Sonotech estimates that 25 hours of maintenance labor is needed annually for its system. This maintenance is performed by a technician at a fully loaded rate of $25 per hour, including overhead and fringe benefits. Replacement parts for the Sonotech system are covered for one year under an equipment warranty. After the initial year, replacement parts are estimated to cost about $1,000 per year. Based on these assumptions, annual maintenance costs are estimated to be $625 for the first year and $1,625 for each year thereafter.

3.3.12 Demobilization Costs

Demobilization includes (1) treatment system shutdown, disassembly, and decontamination; (2) site cleanup and restoration; and (3) transportation and disposal of equipment off site. For this analysis, site demobilization costs for the Sonotech system are assumed to be $0, because the existing incinerator will be demobilized regardless of whether it is retrofit with the pulse combustion burner system.

3.4 Conclusions of Economic Analysis

This analysis presents a cost estimate for treating VOC- and SVOC-contaminated soil with the Sonotech technology. The Sonotech system increases the heat release and mass transfer rates in the combustion process, which results in faster and more complete combustion. As a result, the system is capable of increasing the feedrate by about 15%.

The total estimated capital costs are about $53,900. Of this, about $36,000, or nearly 67%, is for the capital equipment when the Sonotech system is retrofit to an existing incinerator, or specified on new incinerator construction plans. As a result, annual operating and maintenance costs are relatively low because the system uses the labor and energy requirements of the existing incinerator. The Sonotech system has an expected operating life of three years.

Operating conditions, costs, and revenues vary extensively among incinerators. As a result, this analysis provides a worksheet for individual incinerator operators to perform a site-specific cost-benefit analysis. By using real operating costs, an operator can analyze the impact the Sonotech system will have on the incinerator system's profits. Table 5 is provided as a worksheet for the incinerator operator. By inserting the appropriate information, the operator can estimate the profit margin for an incinerator with and without the Sonotech system.

Table 5. Worksheet

Instructions	Operator Estimates[a]	Examples
1. Fill in the current tons per year treated by the incinerator.		40,320
2. Fill in the cost charged to a client to treat 1 ton of waste.		$300
3. Multiply line 1 by line 2 to obtain the current annual revenue realized by the incinerator.		$12,096,000
4. Fill in the current annual operating expenses for the incinerator.		$12,000,000
5. Subtract line 4 from line 3 to obtain the current annual incinerator profit. This figure is used below for comparison purposes.		$96,000
6. Multiply line 1 by 1.15 to obtain the amount of waste that can be treated per year by the incinerator equipped with the Sonotech system.		46,368
7. Fill in the cost charged to a client to treat 1 ton of waste.		$300
8. Multiply line 6 by line 7 to obtain the new annual revenue generated by the incinerator equipped with the Sonotech system.		$13,910,400
9. Fill in the current annual operating expenses for the incinerator.		$12,000,000
10. This line represents the average annual operating costs for the Sonotech system.	$18,000	$18,000
11. Add lines 9 and 10 to obtain the expected annual operating expenses for the incinerator equipped with the Sonotech system.		$12,018,000
12. Subtract line 11 from line 8 to obtain the annual revenue generated by the incinerator equipped with the Sonotech system.		$1,892,400
13. Subtract line 5 from line 12. If the result is positive, it is the additional annual profit that will be generated by installing the Sonotech system. If the amount is negative, it is the additional annual cost that will be incurred by installing the Sonotech system.		$1,796,400

[a]This worksheet is provided to help incinerator operators calculate preliminary cost estimates for using the Sonotech system. To formulate more precise cost estimates, Sonotech can be contacted to obtain direct equipment costs.

Section 4.0
Treatment Effectiveness

Prior to its closure, EPA conducted experimental small-scale and pilot-scale studies at its IRF in Jefferson, AR. The facility housed a pilot-scale RKS and various associated waste handling, emission control, process control, and safety equipment, as well as a bench-scale thermal treatment unit used to conduct thermal treatability studies on a smaller scale. The purpose of the research facility was to support regulatory development and technology assessment under RCRA, TSCA, and CERCLA. Over the past few years, the IRF extended its role by conducting incineration test programs for the Departments of Defense and Energy (DoD and DOE).

The Sonotech pulse combustor test program was performed using the RKS, which consisted of a rotary kiln primary combustion chamber, a transition section, and a fired afterburner chamber. After exiting the afterburner, flue gas flowed through a quench section followed by the primary APCS. The primary APCS for these tests consisted of a venturi/packed-column wet scrubber system, followed by a baghouse. Downstream of the primary APCS, a secondary APCS consisted of a demister, an activated-carbon adsorber, and a HEPA filter. The backup APCS was designed to ensure that organic compound and particulate emissions to the atmosphere are negligible.

During this demonstration, the IRF maintained a complete, analytical laboratory for analysis of VOCs and SVOCs using EPA SW-846 methods. The analytical laboratory was supported by a complete array of flue gas sampling equipment and continuous flue gas analyzers. In addition, the IRF was supported by a full complement of engineering, analytical, and technician staff.

This section discusses the treatment effectiveness of the Sonotech system and provides specific information on the demonstration objectives and approach; demonstration procedures, including waste preparation, demonstration design, sampling and analysis, and quality assurance and quality control (QA/QC); and demonstration results and conclusions.

4.1 Demonstration Objectives and Approach

The general objective of the Sonotech SITE demonstration was to develop data needed to allow an unbiased, quantitative evaluation of Sonotech's claims regarding the pulse combustion technology (see Section 1.4). The focus of the program was to evaluate the developer's claims that the technology lowers combustion pollutant emissions and that it increases an incinerator's treatment capacity. Test program data were also developed to evaluate whether the Sonotech technology affects (1) trace metal partitioning in the incinerator, (2) the leachability of trace metals in incinerator waste streams, and (3) the severity of transient puffs.

To evaluate Sonotech's claims, data were developed to determine whether, compared to convention combustion, applying pulse combustion technology to the IRF RKS resulted in the following:

- Increased incinerator capacity
- Increased POHC DREs
- Decreased flue gas CO emissions
- Decreased flue gas NO_x emissions
- Decreased flue gas soot emissions
- Decreased combustion air requirements
- Decreased auxiliary fuel (natural gas) requirements

The secondary test program objectives required developing data to evaluate whether the application of the Sonotech technology, compared to conventional combustion, resulted in the following:

- Reduced magnitude of transient puffs of CO and TUHC
- Reduced incineration costs
- Significant changes in the distribution of hazardous constituent trace metals among the incinerator discharge streams (kiln bottom ash, scrubber liquor, and baghouse exit flue gas)
- Significant changes in the leachability of TCLP trace metals in kiln ash

The specific procedures taken to achieve the demonstration objectives are described in Section 4.2 below. During the demonstration, observations were also made about the reliability and cost of the Sonotech system. To address the test program objectives, tests at four different incineration system operating conditions were performed. These test conditions are discussed in Section 4.2.

4.2 Demonstration Procedures

During the demonstration, three tests were performed for each of four different incineration system operating conditions, for a total of 12 tests. To evaluate the developer's claims, the test matrix was designed to yield the following types of data:

- Emissions
- POHC DREs
- Metals partitioning
- Metals leachability

The four incineration system operating conditions provided data for the following test conditions:

- Test Condition 1
  - Conventional combustion
  - Typical, baseline, effectively controlled incinerator operation
- Test Condition 2
  - Conventional combustion
  - Maximum waste feed rate under conventional combustion, which typically approaches noncompliance with permit limits
- Test Condition 3
  - Sonotech pulse combustion
  - Feed rate identical to Test Condition 2
- Test Condition 4
  - Sonotech pulse combustion
  - Maximum waste feed rate under Sonotech pulse combustion

4.2.1 Waste Preparation for the Demonstration

The waste feed for all tests consisted of a mixture of contaminated materials from two MGP Superfund sites. One component of the test feed material was a combination of pulverized coal and contaminated sludge waste from the Peoples site in Dubuque, IA. Sludge waste at this abandoned MGP site contained high concentrations of coal tar constituents. The test feed material also consisted of contaminated soil borings and a tar waste obtained from an oil-gasification MGP site in the southeastern U.S.

A mixture of coal and sludge was prepared at the Peoples site in September 1993. The mixture consisted of 65% to 70% coal and 30% to 35% sludge. The mixture was prepared by using a skip loader to place respective proportions of sludge and coal on a pad, then mixing and grinding the combination. The material was then screened through a 2.5-inch-mesh screen, transferred to 20 55-gallon drums and shipped to the IRF.

Initial scoping tests consumed more of the material originally shipped from the Peoples site material than intended. The initial scoping tests were aimed at identifying test material feed rates and incinerator operating conditions that would yield the emissions characteristics desired for the four test conditions. Because the scoping tests consumed too much material, a new mixture was prepared by adding additional coal from the Peoples site to the original mixture; the new coal was added in the proportion of 0.41 kilograms (kg) of coal to 1.0 kg of original Peoples site mixture.

Operational and sample integrity problems resulted from initial attempts to complete one set of demonstration tests (a set includes one test under each of the four planned test conditions with three sets comprising the intended triplicate testing). Because the initial test attempts had to be repeated, additional test feed material had to be identified.

The additional test material consisted of contaminated soil borings and a tar waste from an oil gasification process at an MGP site in the southeastern U.S. The following quantities of waste were shipped to the IRF to complete the demonstration tests:

- Seven 55-gallon drums containing 2,900 pounds (1,320 kg) of soil borings not considered hazardous waste
- Six 55-gallon drums containing 2,700 pounds (1,230 kg) of soil borings contaminated with SVOCs and VOCs, including benzene, toluene, ethylbenzene, and xylenes (BTEX)—having the toxicity characteristic for benzene (hazardous waste code D018)
- Nine 55-gallon drums containing 4,500 pounds (2,050 kg) of tar waste having the characteristic of ignitability (D001) and toxicity for benzene (D018) and cresol (D026).

The feed material used to complete the test program was a combination of the coal-sludge mixture and a mixture of the soil and tar.

For the first incomplete set of demonstration tests, fiberboard containers (cardboard boxes) were packaged to contain 4.5 pounds (2.1 kg) of coal-sludge mixture combined with a benzene-naphthalene spike solution. Components in each fiberboard container included the coal-sludge mixture, the benzene-naphthalene spike, the polyethylene (PE) bottle containing the spike, and the PE bag liner for the container. The total heat content of a filled fiberboard container was about 49,300 British thermal units (Btu) (52.0 megajoules [MJ]). Batch charges—consisting of two of these containers, or almost 100,000 Btu (106 MJ) per batch charge—were fed at variable frequencies to achieve target test conditions.

The second set of demonstration tests was conducted on a mixture that included the newly acquired MGP wastes (which consisted of soil and tar). Exploratory experiments revealed that the fiberboard containers could each hold enough of the soil-tar-coal-sludge mixture and the benzene-naphthalene spike to provide up to 100,000 Btu (106 MJ) per container.

The mixture used was packaged in 1.5-gallon (5.7-liters) fiberboard containers for batch feeding to the RKS. Each container was filled with the following:

- 4.5 pounds (2.1 kg) of coal-sludge mixture
- 3.0 pounds (1.4 kg) of tar
- 3.5 pounds (1.6 kg) of soil (equal weight of hazardous and nonhazardous soil)
- 0.18 pounds (81.6 grams) of spike solution contained in the high density polyethylene (HDPE) bottle
- The polyethylene liner.

The spike solution consisted of a 25-weight-percent solution of naphthalene in benzene (20.4 grams of naphthalene per 81.6 grams of solution). To prepare each fiberboard container, it was first filled with the specified weight of each test material feed component. The bottle of spike mixture was then imbedded in the feed mixture, and the container's double-thick PE liner was sealed with a plastic tie. The fiberboard container was then closed and sealed with paper packaging tape.

4.2.2 Demonstration Design

As discussed in the introduction to this section, tests were performed under four different incineration operating conditions to address the demonstration objectives.

The waste feed was prepared as described in Section 4.2.1 and was batch fed to the RKS via its ram-feed system. The target feedrate for each of the four test conditions were as follows:

- Test Condition 1: 61.1 lb/hr (27.8 kg/hr)
- Test Conditions 2 and 3: 74.7 lb/hr (33.9 kg/hr)
- Test Condition 4: 84.0 lb/hr (38.2 kg/hr)

The test feed frequency was designed to operate within the IRF's permit-required CO emission level of 100 ppm on a 1-hour rolling average basis. A 50-ppm, 1-hour rolling average was used as the waste feed cutoff point to ensure a safety margin. Kiln exit gas temperature was nominally 1,700 degrees Fahrenheit (°F) (927 degrees Celsius [°C]) and the oxygen concentration was nominally 10%. Afterburner exit gas was nominally 2,000°F (1,090°C) and the oxygen concentration was nominally 8%.

Beginning on the day before each demonstration test, the RKS was fired with natural gas to bring it to steady state operation at the desired conditions. The Sonotech burner was also fired prior to test days scheduled for pulse combustion testing, although pulsations were not initiated until the test. Test material feed was then initiated, and steady RKS operation was established. Kiln and afterburner fuel and air flows, along with secondary combustion air flow, were controlled to give the desired temperature and excess air conditions. Flue gas sampling (see Section 4.2.3) began no sooner than 1.5 hours after the initial waste feed. Feed was continued until flue gas sampling was completed. The ash auger transfer system on the kiln continuously removed kiln ash from the kiln ash hopper and deposited it into clean 55-gallon drums.

After each test, ash from each test was weighed and sampled for analyses. Baghouse ash and scrubber liquor samples were also collected at the end of each test for analyses. Analytical protocols are described below in Section 4.2.3.

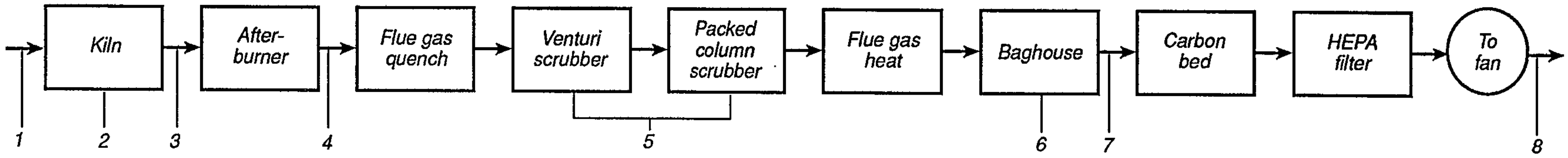
For all tests, the incinerator operating parameters were recorded using an electronic data acquisition system; operating parameters were also recorded manually at a minimum of every 15 minutes.

4.2.3 Sampling and Analysis Program

The Sonotech technology demonstration was conducted over a 4-month period. This section describes the sampling and analysis program associated with the demonstration. It also discusses field and laboratory QA/QC procedures, deviations from methods and procedures outlined in the Sonotech quality assurance project plan (QAPP) (Acurex and PRC 1994), and any impact the deviations may have had on project objectives.

Figure 3 depicts RKS sampling types, locations, and methods. For all tests, the following sampling activities were performed:

- Obtain a composite sample of the kiln ash discharge
- Obtain a composite sample of the scrubber system liquor
- Obtain a composite sample of the baghouse flyash
- Continuously measure the following components of the flue gas:
  - oxygen concentrations in the kiln exit flue gas
  - oxygen, CO, carbon dioxide (CO_2), NO_x, and TUHC concentrations in the afterburner exit flue gas
  - oxygen, CO_2, and NO_x concentrations in the baghouse exit flue gas
  - oxygen and CO concentrations in the stack gas
- Collect a gram-sized sample of afterburner exit particulate using the EPA Method 17 sampling train
- Sample flue gas at the afterburner exit and baghouse exit for trace metals using the EPA Method 29 multiple metals sampling train
- Sample flue gas at the baghouse exit for mercury using EPA Method 101A



Sampling points	Total feed material	Kiln ash	Scrubber liquor	Bag-house ash	O_2	CO	CO_2	NO_x	Heated TUHC	High-volume Method 17, particulate	EPA multiple metal train, test trace metals	Method 101A mercury	Method 0010, test semivolatile POHCs and PAHs	Method 0030, volatile organic constituents	Method 23, PCDD/PCDF	Method 5, particulate and HCl
1. Feed	X															
2. Kiln ash discharge		X														
3. Kiln exit flue gas					X											
4. Afterburner exit flue gas					X	X	X	X	X	X	X		X	X		
5. Scrubber liquor			X													
6. Baghouse hopper				X												
7. Baghouse exit flue gas					X		X	X			X	X	X	X	X	X
8. Stack gas					X	X										X

Figure 3. Block diagram of Rotary Kiln System sampling locations, types, and methods.

- Sample flue gas at the afterburner exit and baghouse exit for semivolatile POHCs and other polynuclear aromatic hydrocarbon (PAH) constituents using the EPA Method 0010 train

- Sample flue gas at the afterburner exit and baghouse exit for VOCs using the EPA Method 0030 volatile organic sampling train (VOST)

- Sample flue gas at the baghouse exit for PCDDs and PCDFs using EPA Method 23

- Sample flue gas at the baghouse exit and the stack for particulate and hydrogen chloride using EPA Method 5 (stack sampling is needed to comply with IRF permit requirements)

No feed material sample was collected for any test. Instead, feed material component samples were collected for analysis by preparing all test feed material fiberboard containers to contain four feed components and a benzene-naphthalene spike. The four components were added sequentially to each fiberboard container: a coal-fortified coal-sludge mixture from the Peoples site, two different mixtures of soil borings from an MGP Superfund site in the southeastern U.S., and an oil gasification process tar from the southeastern MGP site. The coal-sludge and soil components were each mixed to ensure that all fiberboard containers were filled with the most uniform feed composition that could be practically achieved. Tar from the site was collected in a manner that produced a uniform composition among all shipping containers of tar received and targeted for use in demonstration tests.

During the test program, three samples of each feed component were collected—one for each of the three sets of tests comprising the triplicate test program. Each set of tests consisted of four tests—one at each of the four specified conditions. About midway through the packaging exercise for each test set, one fiberboard container was charged with only the coal-sludge mixture and was set aside. Another container was filled with each soil component; the soil components were then mixed by hand-kneading the plastic bag liner, and the container was then set aside. Near the midpoint of adding tar to the fiberboard containers of coal-sludge and soil, a 1-liter sample container was filled with tar to represent the tar component sample for the test set. The samples were then taken to the on-site laboratory for subsequent aliquot splitting and aliquot preservation for shipment or analysis.

Kiln bottom ash was continuously removed from the RKS ash pit by the ash auger system and was deposited in a 55-gallon drum. Kiln ash was collected in one drum during initiation of each test run before the start of flue gas sampling. A new ash collection drum was used to collect kiln ash during the flue gas sampling. The flue gas sampling time period is the time of the actual test run. After the flue gas sampling was completed, the collection drum was removed. The entire fraction of kiln ash collected during the sampling period was split into two parts that were about equal. One part was stored, as is, in appropriate jars. Aliquots for volatile organics analysis were drawn from this fraction. The remaining ash was ground overnight in a 55-gallon rotating-drum grinding machine. Aliquots for ash analyses other than volatile organics were drawn from the ground ash fraction. The ash was ground to ensure maximum homogeneity in the collected sample. The unground fraction was later ground by the external laboratory conducting the VOC analyses.

For all test runs, the RKS scrubber system was operated at as close to total recirculation (zero blowdown) as possible. After each test run, the scrubber system was drained to a collection tank. Composite post-test scrubber liquor samples were collected from a tap in the recirculation loop immediately before draining the system. After draining, the scrubber system was recharged with fresh makeup water for the next test run. For each test run, pre-test scrubber liquor samples were collected from the recirculation loop tap immediately before the start of test material feeding for the test.

Gram quantities of baghouse ash were collected for all tests. The entire amount collected was used for analysis.

The Method 5 trains for particulate and hydrogen chloride collection had dilute caustic-filled impingers (0.1 normal sodium hydroxide). Both hydrogen chloride and chlorine from the flue gas were collected in the impingers. This provided a conservative estimate of hydrogen chloride concentrations (hydrogen chloride plus chlorine) and satisfied test program objectives. Over about a 1-hour period, a nominal 50-cubic-foot (ft^3) (1.4-cubic-meter [m^3]) sample was collected at the two locations sampled. The Method 0010, Method 23, Method 101A, and multiple metals trains sampled 100 ft^3 (2.8 m^3) of flue gas over a 3-hour period. Because mercury was measured using a separate sampling train, the permanganate impingers for mercury collection were not used in the multiple metals trains, and sample recovery steps from these trains—specified for eventual mercury analysis—were not performed. Four Method 0030 trap pairs each sampled 20 liters of flue gas. Four additional trap pairs were taken as insurance against trap breakage.

Throughout the demonstration CEM data were recorded continuously on strip charts and by two automatic data acquisition systems. Figure 4 depicts the generalized flue gas and CEM gas flow.

Test program samples were analyzed for matrix-specific combinations of the following:

- Semivolatile POHCs and PAH constituents
- Volatile organic constituents
- PCDDs/PCDFs
- Contaminant trace metals
- Total organic carbon
- Chloride
- Moisture
- Heat content
- Carbon, hydrogen, oxygen, nitrogen, and sulfur

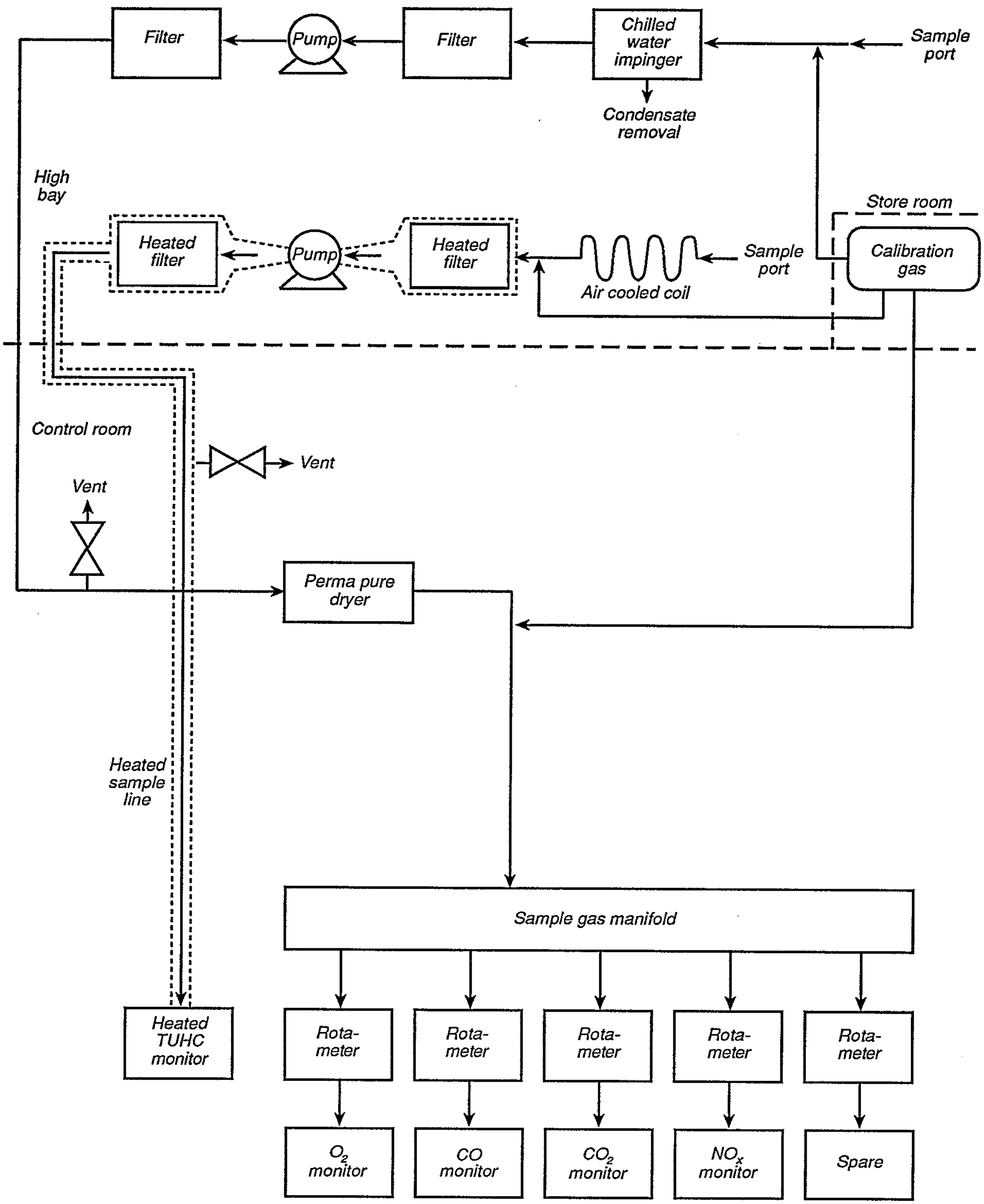


Figure 4. Generalized flue gas and CEM gas flow schematic.

Table 6 lists volatile organic, semivolatile organic, and trace metal target analytes. Table 7 summarizes the number of test program sample analyses. As indicated in Table 7, samples of most sample matrices were analyzed for each of the 12 test runs (three runs at each of four test conditions) completed. However, as the test feed material was the same for the 12 test runs, only four samples of each of the components of this material, including one duplicate pair, were collected and analyzed. Also prepared were TCLP leachates of each test's kiln ash, post-test scrubber liquor, baghouse ash, and four of each of the three feed components (plus a duplicate series of samples). Table 8 summarizes analytical protocols for the various samples. The sample aliquot schedules and custody, storage, and shipment procedures were followed according to test protocols.

4.2.4 Quality Assurance and Quality Control Program

QC checks and procedures were an integral part of the Sonotech SITE demonstration to ensure that QA objectives were met. These checks and procedures focused on (1) the collection of representative samples that were free of external contamination and (2) the analysis of comparable data. Two kinds of QC checks and procedures were conducted during the demonstration: (1) checks controlling field activities, such as sample collection and shipping, and (2) checks controlling laboratory activities, such as extraction and analysis. A detailed discussion of the QA/QC program is provided in the SITE Program Evaluation of the Sonotech Pulse Combustion Burner Technology report (EPA 1996).

4.3 Demonstration Results and Conclusions

This section discusses the operating conditions, demonstration results, data quality, and conclusions of the SITE demonstration of the Sonotech system. The SITE demonstration provides the most extensive Sonotech performance data to date and serves as the foundation for conclusions on the system's effectiveness and applicability. Demonstration results have been supplemented by information provided by the vendor.

4.3.1 Operating Conditions

Four incineration system operating conditions were tested during the demonstration (see Section 4.2). After preparing the waste feed (see Section 4.2.1), the test material was batch fed to the RKS ram-feed system. The test feedrate (or charge frequency) and RKS operating conditions were determined from scoping tests and are described in detail later in this section. One factor influencing the maximum feedrate was the IRF permit limit maximum CO emission level of 100 ppm on a 1-hour rolling average basis. When a relatively high heat content material is being fed, the maximum allowable waste feedrate is established based on the incidence of puffs of incompletely combusted organic constituents (primarily CO and TUHC) that survive the burner. A 50-ppm, 1-hour rolling average was used as the waste feed cutoff point to ensure that the CO permit level was not violated. For example, a feedrate that results in routine stack gas CO spikes of over 300 ppm, lasting 30 seconds or more, and also leading to a 1-hour rolling average flue gas CO levels approaching 50 ppm would be the maximum tolerated to be characterized as an acceptable operation. The temperature of the kiln exit gas was nominally 1,700°F (927°C), and the oxygen concentration was nominally 10%. Afterburner exit gas temperature was nominally 2,000°F (1,090°C) and oxygen concentration was nominally 8%.

Scoping tests were performed to define the waste feedrates corresponding to each condition. The most critical conditions to define were those for Test Condition 2 and Test Condition 4. Both of these are defined to be conditions of borderline acceptable operation. The waste feedrates for these conditions were established during scoping tests by increasing the waste feedrate to the kiln until one or both of the following conditions occurred:

- An unacceptable level and frequency of CO spikes in the afterburner exit flue gas occurred, causing the hourly average CO levels to approach 50 ppm corrected to 7% oxygen
- Difficulty in controlling kiln exit gas temperature to the desired target level

The feedrate for each critical condition was then established to be just below that associated with one or both of the above conditions.

The point at which the waste feedrate could not be varied deserves emphasis. All demonstration test waste feed material was packaged into cubical fiberboard containers. Each container was filled with 11.2 pounds of waste and POHC spike mixture. The only means of varying waste feedrate was by varying the frequency of container charging to the kiln. In addition, other constraints were placed on incinerator operation in establishing waste feedrates. For example, the minimum heat input supplied to the kiln by auxiliary fuel (natural gas) had to be at least 500 thousand British thermal units per hour (kBtu/hr) (147 kW). This constraint is an operational safety limit at the IRF. It was established to ensure that a safe combustion environment always existed in the kiln.

The target feedrates for each of the four test conditions arising from the scoping tests are given in Table 9. The table indicates not only the target feedrate, but also the charge frequency for each test condition that resulted in that feedrate target. A discussion of scoping test data to show that the selected targets met the operating condition objectives would be appropriate here. However, scoping test data reflect shorter term incinerator operation than occurred during actual demonstration tests, and a more extensive data base of incinerator operating conditions was developed while completing the actual demonstration tests. Therefore, discussion which shows that the selected target feedrates met the operating condition objectives is presented below.

Beginning on the day before each demonstration test, the RKS was brought to steady operation at the desired conditions by firing only natural gas. The Sonotech burner was also fired prior to pulse combustion test days, although pulsations were not begun until the test day. On the test days, waste material was fed into the system, and steady RKS operation was reestablished. Com-

Table 6. Target Analytes

Volatile Organic Analytes	
Benzene	cis-1,3-Dichloropropene
Bromodichloromethane	trans-1,3-Dichloropropene
Bromoform	Ethylbenzene
Carbon tetrachloride	Methylene chloride
Chlorobenzene	Styrene
Chlorodibromomethane	1,1,2,2-Tetrachloroethane
Chloroethane	Tetrachloroethene
Chloroform	Toluene
Chloromethane	1,1,1-Trichloroethane
Dibromomethane	1,1,2-Trichloroethane
1,1-Dichloroethane	Trichloroethene
1,2-Dichloroethane	1,2,3-Trichloropropane
1,1-Dichloroethene	Vinyl chloride
trans-1,2-Dichloroethene	Xylenes (total)
1,2-Dichloropropane	
Semivolatile Organic Analytes	
Acenaphthene	Dibenz(a,h)anthracene
Acenaphthylene	Fluoranthene
Anthracene	Fluorene
Benzo(a)anthracene	Indeno(1,2,3-cd)pyrene
Benzo(b)fluoranthene	2-Methylnaphthalene
Benzo(k)fluoranthene	Naphthalene
Benzo(ghi)perylene	Phenanthrene
Benzo(a)pyrene	Pyrene
Chrysene	
Trace Metal Analytes	
Antimony	Cadmium
Barium	Chromium
Beryllium	Lead
Mercury	

Table 7. Test Program Sample Analysis Summary

Sample Matrix	Number of Analyses: Semivolatile POHCs and other PAHs	Volatile Organic Constituents	Trace Metals[a]	Mercury	PCDDs/ PCDFs	Chloride	Total Organic Carbon
Coal-sludge feed component							
Test sample	4	4	4	4			
Split sample	1	1	1	1			
Matrix spike	1	1	1	1			
Spike duplicate	1	1	1	1			
Soil feed component							
Test sample	4	4	4	4			
Split sample	1	1	1	1			
Matrix spike	1	1	1	1			
Spike duplicate	1	1	1	1			
Tar feed component							
Test sample	4	4	4	4			
Split sample	1	1	1	1			
Matrix spike	1	1	1	1			
Spike duplicate	1	1	1	1			

(continued)

[a]Except mercury.

Table 7. Continued

Sample Matrix	Number of Analyses: Semivolatile POHCs and other PAHs	Volatile Organic Constituents	Trace Metals[a]	Mercury	PCDDs/ PCDFs	Chloride	Total Organic Carbon
Kiln ash							
Test sample	12	12	12	12			
Split sample	2	2	2	2			
Matrix spike	2	2	2	2			
Spike duplicate	2	2	2	2			
Pre-test scrubber liquor							
Test sample	12	12	12	12			
Split sample	1	1	1	1			
Matrix spike	1	1	1	1			
Spike duplicate	1	1	1	1			
Post-test scrubber liquor							
Test sample	12	12	12	12			
Split sample	2	2	2	2			
Matrix spike	2	2	2	2			
Spike duplicate	2	2	2	2			
Baghouse ash							
Test sample	12	12	12	12			
Split sample	2	2	2	2			
Matrix spike	2	2	2	2			
Spike duplicate	2	2	2	2			
Afterburner exit particulate							
Test sample	12						12
Split sample							2
Matrix spike							2
Spike duplicate							2
TCLP leachate							
Test feed material			4	4			
Kiln ash			12	12			
Post-test scrubber liquor			12	12			
Baghouse ash			12	12			
Method blank			2	2			
Split sample			4	4			
Matrix spike			4	4			
Spike duplicate			4	4			
Method 0010 train							
Test sample	24						
Field blank	3						
Matrix spike	3						
Spike duplicate	3						
Method 0030 train							
Test sample trap pair[b]		72					
Field blank		12					
Trip blank		6					
Matrix spike		6					
Method 23 train							
Test sample					12		
Field blank					1		

(continued)

[a]Except mercury.
[b]Four trap pairs sampled per location per test. Three trap pairs analyzed; fourth trap pair for breakage contingency.

Table 7. Continued

Sample Matrix	Semivolatile POHCs and other PAHs	Volatile Organic Constituents	Trace Metals[a]	Mercury	PCDDs/ PCDFs	Chloride	Total Organic Carbon
	Number of Analyses						
Multiple metals train							
Front half							
Test sample			24				
Field blank			3				
Matrix spike			3				
Spike duplicate			3				
Back half							
Test sample			24				
Field blank			3				
Matrix spike			3				
Spike duplicate			3				
Method 101A train							
Test sample				12			
Field blank				2			
Matrix spike				2			
Spike duplicate				2			
Method 5 train impingers							
Test sample						24	
Split sample						2	
Field blank						2	
Matrix spike						2	
Spike duplicate						2	
Total	132	183	207	159	13	32	18

[a]Except mercury.

Table 8. Analytical Protocols

Sample	Parameter	Analysis Method	Frequency
Test feed material components	Proximate analysis (moisture, volatile matter, fixed carbon, ash)	ASTM D-5142	1/test mixture
	Elemental analysis C, H, O, N, S Cl	 ASTM D-3176 ASTM E-442	1/test mixture
	Heating value	ASTM D-3286	1/test mixture
	Semivolatile organic constituents	Soxhlet extraction by Method 3540A, GC/MS analysis by Method 8270A[a]	1/test mixture
	Volatile organic constituents	Purge and trap GC/MS by Method 8260[a]	1/test mixture
	Trace metals[b]	Digestion by the Multiple Metals Filter Method[c] or Method 3051[a], ICP analysis	1/test mixture
	Mercury	Digestion and CVAAS analysis by Method 7471[a]	1/test mixture
	TCLP extraction	Method 1311[a]	1/test mixture
Test feed TCLP leachate	Trace metals[b]	Digestion by Method 3015, ICP or GFAAS analysis	1/test mixture
	Mercury	Digestion and CVAAS analysis by Method 7470[a]	1/test mixture
Kiln ash	Semivolatile organic constituents	Soxhlet extraction by Method 3540A, GC/MS analysis by Method 8270A[a]	1/test run
	Volatile organic constituents	Purge and trap GC/MS by Method 8260[a]	1/test run
	Trace metals[b]	Digestion by the Multiple Metals Filter Method[c], ICP analysis	1/test run
	Mercury	Digestion and CVAAS analysis by Method 7471[a]	1/test run
	TCLP extraction	Method 1311[a]	1/test run
Kiln ash TCLP leachate	Trace metals[b]	Digestion by Method 3015, ICP or GFAAS analysis	1/test run
	Mercury	Digestion and CVAAS analysis by Method 7470	1/test run
Pre-test scrubber liquor	Semivolatile organic constituents	Extraction by Method 3520A, GC/MS analysis by Method 8270[a]	1/test run
	Volatile organic constituents	Purge and trap GC/MS by Method 8260[a]	1/test run
	Trace metals[b]	Digestion by Method 3015, GFAAS or ICP analysis	1/test run
	Mercury	Digestion and CVAAS analysis by Method 7470	1/test run
Post-test scrubber liquor	Semivolatile organic constituents	Extraction by Method 3520A, GC/MS analysis by Method 8270A[a]	1/test run
	Volatile organic constituents	Purge and trap GC/MS by Method 8260[a]	1/test run
	Trace metals[b]	Digestion by Method 3015, GFAAS or ICP analysis	1/test run
	Mercury	Digestion and CVAAS analysis by Method 7470	1/test run
	TCLP extraction	Method 1311[a]	1/test run
Scrubber liquor TCLP leachate	Trace metals[b]	Digestion by Method 3015, ICP or GFAAS analysis	1/test run
	Mercury	Digestion and CVAAS analysis by Method 7470	1/test run
			(continued)

[a]SW-846 (EPA 1992).
[b]Sb, Ba, Be, Cd, Cr,.and Pb.
[c]40 CFR 266, App. IX.

Table 8. Continued

Sample	Parameter	Analysis Method	Frequency
Baghouse ash	Semivolatile organic constituents	Soxhlet extraction by Method 3540A, GC/MS analysis by Method 8270A[a]	1/test run
	Volatile organic constituents	Purge and trap GC/MS by Method 8260[a]	1/test run
	Trace metals[b]	Digestion by the Multiple Metals Filter Method[c], ICP analysis	1/test run
	Mercury	Digestion and CVAAS analysis by Method 7471[a]	1/test run
	TCLP extraction	Method 1311[a]	1/test run
Baghouse ash TCLP leachate	Trace metals[b]	Digestion by Method 3015, ICP or GFAAS analysis	1/test run
	Mercury	Digestion and CVAAS analysis by Method 7470	1/test run
Afterburner exit particulate	Semivolatile organic constituents	Soxhlet extraction by Method 3540A, GC/MS analysis by Method 8270A	1/test run
	Total organic carbon	Method 9060[a]	1/test run
Afterburner exit flue gas	Semivolatile organic constituents	Soxhlet extraction of Method 0010 samples by Method 3540A, GC/MS analysis by Method 8270A[a]	1/test run
	Volatile organic constituents	Purge and trap GC/MS analysis of Method 0030 samples by Method 5041[a]	3 trap pairs/test run
	Trace metals[b]	Digestion of multiple metals train samples by Multiple Metals Method[c] or Method 3015[a], GFAAS or ICP analysis	1/test run
Baghouse exit flue gas	Semivolatile organic constituents	Soxhlet extraction of Method 0010 samples by Method 3540A, GC/MS analysis by Method 8270A[a]	1/test run
	Volatile organic constituents	Purge and trap GC/MS analysis of Method 0030 samples by Method 5041[a]	3 trap pairs/test run
	PCDDs/PCDFs	GC/MS analysis of Method 23 samples by Method 8290[a]	1/test run
	Trace metals[b]	Digestion of multiple metals train samples by Multiple Metals Method[c] or Method 3015[a], GFAAS or ICP analysis	1/test run
	Mercury	Sample preparation by Method 101A[d], CVAAS analysis by Method 7470[a]	1/test run
	Particulate	Method 5[e]	1/test run
	HCl	IC analysis of impinger solutions by Method 9057[c]	1/test run
Stack gas	Particulate	Method 5[e]	1/test run
	HCl	IC analysis of combined impinger solution by Method 9057[a]	1/test run

[a]SW-846 (EPA 1992).
[b]Sb, Ba, Be, Cd, Cr, and Pb.
[c]40 CFR 266, App. IX.
[d]40 CFR 61, App. B.
[e]40 CFR 60, App. A.

Table 9. Target Feedrates

Test Condition	Description	Target Feedrate, lb/hr (kg/hr)	Charge Frequency (minutes between charges)
1	Baseline, typical incinerator operation	61.1 (27.8)	11
2	Maximum feedrate operation	74.7 (33.9)	9
3	Sonotech pulse combustor on, feedrate same as in 2	74.7 (33.9)	9
4	Maximum feedrate operation with Sonotech pulse combustor on	84.0 (38.2)	8

Notes: kg/hr = Kilograms per hour
lb/hr = Pounds per hour

bustion air flows and kiln and afterburner auxiliary burner fuel (natural gas) were controlled to achieve the desired temperature and excess air conditions. Flue gas sampling was started no sooner than 1.5 hours after the start of waste material feed to the system. The waste feed was continued until all flue gas sampling was completed. For all tests, the scrubber system was operated at its nominal design settings (see Table 10) and at as close to total recirculation (zero to minimum blowdown) as possible. The kiln ash auger transfer system continuously removed kiln ash from the hopper and deposited it into clean 55-gallon drums.

After completing flue gas sampling for each test, test material feed was stopped. The incinerator was then continually fired with natural gas for two hours or until the kiln was visibly clear of ash material, whichever time period was longer. Ash collected from each test's ash drum was weighed and sampled. Scrubber liquor samples were collected from a tap in the recirculation loop before the scrubber liquor loop was drained. The contents of the baghouse hopper (collected fly ash) were emptied into a collection bucket and transferred to a sample container. The entire amount collected was used as the baghouse ash sample. After the scrubber liquor loop was recharged with fresh makeup water, the incinerator was either turned off (during weekends) or operated overnight by firing natural gas to produce steady-state conditions for the next test.

For all tests, the incinerator operating parameters noted in Table 11 were recorded at intervals of no longer than 15 minutes. Table 12 summarizes the average operating conditions achieved for the various components of the RKS for each of the 12 tests. Test Conditions 1 and 2 were without the Sonotech system in operation. The subsections below discuss the pulse combustion system, operating parameters, and system maintenance.

Tests 1 through 12 were performed in chronological order. Tests 1, 2, 3, and 4 were the first tests at Test Conditions 1, 2, 3, and 4, respectively. The split of auxiliary fuel feedrates between the kiln and the afterburner was not exactly as desired during Test 3. Specifically, the total auxiliary fuel feedrate to the kiln, at 388 kBtu/hr for Test 3, was lower than the 494 kBtu/hr for Test 2, and the auxiliary fuel feedrate to the afterburner, at 1,200 kBtu/hr, was greater than the 1,060 kBtu/hr for Test 2. The auxiliary fuel distributions for Test 5, the second Test Condition 3 test, with a total kiln feedrate of 494 kBtu/hr and an afterburner feedrate of 1,020 kBtu/hr, were more nearly those for Test 2. Thus, Test 5 was chosen to represent Test Condition 3. Because these were the first tests at each respective test condition tested, the feedrate and other incinerator operating conditions for these tests were used as targets for subsequent tests at each respective condition.

Test 1 was performed at a waste feedrate of 61.6 lb/hr, achieved by charging a waste container to the kiln every 11 minutes. An additional 635 kBtu/hr of auxiliary fuel was needed in the kiln to maintain the desired kiln exit gas temperature of nominally 1,700°F (927°C). Average afterburner exit CO levels were an acceptable 9 ppm corrected to 7% oxygen. Over the duration of this test, four CO spikes of 100 ppm or greater occurred, corresponding to an average of a spike every fourth charge. Of the four spikes experienced, the largest peaked at about 540 ppm, one peaked at about 370 ppm, and two peaked at about 100 ppm.

For Test 2, the waste feed charge frequency was increased to one charge every 9 minutes, giving an increased waste feedrate of 72.3 lb/hr. Because the waste had considerable heating value, less auxiliary fuel was required to maintain the target kiln exit gas temperature. Thus, the auxiliary fuel feedrate to the kiln was decreased to the minimum allowable, at 494 kBtu/hr (nominally 500 kBtu/hr). Average afterburner exit gas CO was significantly increased 40 ppm, corrected to 7% oxygen. A higher waste feedrate for this condition, by increasing charge frequency to one charge every 8 minutes, was not possible because kiln exit gas temperature would have increased to well above the desired target. Temperature control by decreasing auxiliary fuel feedrate was not possible as this was already at the allowed minimum. It was decided that feedrate changes of less than about 10%, corresponding to feed charge frequency changes of integral minutes, would not be considered significant. Over the duration of flue gas sampling for Test 2, nine CO spikes of over 100 ppm occurred, corresponding to an average of a spike every two to three charges. Of these nine, six drove the CO monitor to its full-scale reading of 630 ppm, one peaked at about 550 ppm, one at about

Table 10. IRF RKS Air Pollution Control System Operating Parameters

Venturi liquor flowrate	20 gallons per minute (gpm) (76 liter per minute [L/min])
Venturi pressure drop	25 inches of water (6.2 kilopascal [kPa])
Packed tower liquor flowrate	30 gpm (115 L/min)
Scrubber liquor temperature	120°F (49°C)
Scrubber blowdown rate	0 gpm (0 L/min) or minimum operable rate

Notes: L/min = Liter per minute
kPa = Kilopascal
gpm = Gallon per minute

Table 11. Measured Incinerator Operating Parameters

Temperature
Rotary kiln exit gas
Rotary kiln solids at 4 axial locations
Afterburner exit gas
Quench inlet gas
Quench exit gas
Scrubber exit gas
Baghouse exit gas
Stack gas
Recirculating quench/scrubber liquor
Scrubber blowdown liquor
Flowrates
Rotary kiln main burner natural gas feed
Sonotech burner natural gas feed
Afterburner natural gas feed
Rotary kiln main burner combustion air
Sonotech burner combustion air
Afterburner combustion air
Stack combustion gas
Venturi scrubber liquor
Packed tower scrubber liquor
Scrubber blowdown liquor
Scrubber makeup liquor
Pressures
Rotary kiln chamber
Afterburner chamber
Venturi scrubber pressure drop
Packed tower scrubber pressure drop
Baghouse pressure drop
Other
Scrubber liquor pH
Cumulative test material weight fed

220 ppm, and one at about 150 ppm. As noted above, the average CO level over the duration of flue gas sampling was 40 ppm, corrected to 7% oxygen. Increasing waste feedrate by increasing feed charge frequency to one charge every 8 minutes would also have increased the frequency of CO spikes and, in turn the average CO level. At 40 ppm, corrected to 7% oxygen, the average CO was near the defined test operational limit of 50 ppm, corrected to 7% oxygen. In summary, the waste feedrate for Test 2 was indeed the maximum that could be achieved under conventional combustion. Based on many years of testing experience at the IRF, operator judgement was that further increases in feedrate beyond that achieved would have resulted in a significantly increased kiln exit gas temperature and a much increased frequency of CO spikes in the afterburner exit gas, possibly giving rise to average afterburner exit gas CO levels above the 50-ppm operational limit.

For Test 5, representing Test Condition 3 (with the Sonotech system operating), the waste feed charge frequency was held at one charge every 9 minutes, giving a waste feedrate of 74 lb/hr, essentially the same as for Test 2 at Test Condition 2, as desired. Kiln exit gas temperature remained at nominally 1,700°F (927°C), with auxiliary fuel feedrate to the kiln (now apportioned between the Sonotech burner and the kiln main burner) remaining at nominally 500 kBtu/hr. Over the duration of flue gas sampling for Test 5, eight CO spikes over 100 ppm occurred, corresponding to an average, again, of a spike every two to three charges. Of the eight spikes, two were at the instrument full-scale of 630 ppm, one peaked at about 220 ppm, two at about 180 ppm, and one at about 150 ppm. Thus, while the frequency of CO spikes for Test Condition 3 was nearly the same as for Test Condition 2, average peak levels were lower for Test Condition 3. Accordingly, the average CO for Test 5 was lower, at 16 ppm, corrected to 7% oxygen.

For Test 4, representing Test Condition 4 (with the Sonotech system operating), the waste feed charge frequency was further increased to one charge every 8 minutes, giving an increased feedrate for this test of 83.8 lb/hr. Because the IRF operations staff had very limited experience with the Sonotech system, no prior experience base was available to guide expectations regarding the incinerator's response to increasing waste feedrate above the maximum achievable under conventional combustion. Upon increasing waste feedrate, the kiln exit gas temperatures remained at the target of about 1,700°F (927°C), with kiln auxiliary fuel flow, while slightly decreased, still at nominally 500 kBtu/hr. This increased waste feedrate, while maintaining kiln temperatures using nominally the same minimum auxiliary fuel feed to the kiln, was only possible by having the Sonotech system in operation. Over the duration of flue gas sampling for Test 4, eight CO spikes over 100 ppm occurred, corresponding to a spike every third charge. Of the eight spikes, three were at the instrument full-scale level of 630 ppm, and one each peaked at about 420, 380, 300, 260, and 220 ppm. The corresponding average afterburner exit gas CO was 17 ppm, corrected to 7% oxygen. Thus, in comparison to Test 2, an increased waste feedrate could be maintained, at more acceptable afterburner exit gas CO levels, only by employing the Sonotech burner system.

4.3.1.1 Sonotech Cello® Pulse Combustion System

The general principles of pulse combustion and the Sonotech pulse combustion technology are described in Section 1.4. The pulse combustor used in this test program was fabricated to meet the needs of the IRF RKS. The combustor was approximately 6 feet (1.8 meters) long and 4 feet (1.2 meters) wide and was supported by a structure designed to align its axis into the available port in the incinerator. The pulse combustor was also fitted with a flanged plate that enabled it to be attached to the incinerator. The unit consisted of a tunable pulse combustor, fuel and air trains with flow meters, and a control system. The combustor was designed to deliver approximately 250,000 Btu/hr (74 kW) to the kiln.

4.3.1.2 Operating Parameters

The tests were configured so that the Sonotech pulse combustor would deliver a heat input of roughly 15% to 20% of the typical heat input to the kiln. Exploratory tests revealed that a resonance was achieved in the kiln chamber when the pulse combustor was operated at 300 ± 20 Hertz (Hz). Based on results of the exploratory tests, the nominal settings for all tests with the pulse combustor operating were as follows: natural-gas flow rate of 200 standard cubic feet per hour (5.7 standard cubic meters

Table 12. Operating Data and Results

Parameter	Test Condition (Average Values) 1: Conventional Combustion Baseline Feedrate	2: Conventional Combustion Maximum Feedrate	3: Pulse Combustion Baseline Feedrate	4: Pulse Combustion Maximum Feedrate
Waste feedrate, lb/hr	61.0	72.8	73.6	82.4
Waste heating value, Btu/lb	8,750	8,750	8,750	8,750
Rotary kiln exit gas temperature, °F	1,720	1,730	1,700	1,700
Afterburner exit gas temperature, °F	2,000	2,000	2,000	2,000
Heat input, kBtu/hr				
Waste feed	522	601	628	697
Kiln auxiliary fuel				
Main burner	659	506	282	205
Sonotech burner	0	0	200	200
Total kiln	659	506	482	405
Afterburner auxiliary fuel	1,010	1,040	1,094	1,082
Total auxiliary fuel	1,670	1,540	1,580	1,480
Total system heat input, kBtu/hr	2,190	2,150	2,200	2,180
Kiln ash heating value, Btu/lb	1,240	1,320	<500	1,430
Combustion air, dscf/hr	41,700	39,500	37,500	38,400
Afterburner exit CO, ppm at 7% O_2	15	20	14	18
Afterburner exit NO_x, ppm at 7% O_2	90	82	77	78
Afterburner soot emission rate, mg/dscm at 7% O_2 (TOC as percent of particulate)	<1.3	1.9	<1.0	1.3

Notes: Each value (except condition 1 afterburner exit soot emissions) is the average of results for three test runs.

lb/hr = Pounds per hour
Btu/lb = British thermal units per pound
kBtu/hr = Thousand British thermal units per hour
dscf/hr = Dry standard cubic feet per hour
ppm = Parts per million
mg/dscm = Milligram per dry standard cubic meter
CO = Carbon monoxide
NO_x = Nitrogen oxide
O_2 = Oxygen
TOC = Total organic carbon

per hour), air flow rate of 2,000 standard cubic feet per hour (57 standard cubic meters per hour), and a pulsation frequency of 300 Hz.

4.3.1.3 System Maintenance

Scoping and demonstration test runs were performed at the IRF from May through October 1994. During this time, the Sonotech pulse combustion system experienced no operational problems. Routine maintenance during this period involved only visual inspection of the burner system prior to start-up. No other special maintenance was required.

4.3.2 Results and Discussion

As noted in Section 4.2.3, composite feed material samples were not collected and analyzed for each test. Instead, samples of each feed component were collected for analysis. Thus, the composition of the test program feed material was defined based on measured component composition and component proportions in the integrated feed. Table 13 summarizes the feed component VOC and SVOC concentrations measured. Table 14 lists the metal concentrations in the various feed materials.

4.3.2.1 Primary Objective

The primary objective of the demonstration was to develop test data to evaluate the treatment efficiency of the Sonotech system compared to conventional combustion. Test data were evaluated to determine if the Sonotech system accomplished the following developer claims:

(1) Increased incinerator capacity

(2) Increased the DRE of POHCs

Table 13. Concentrations of Volatile and Semivolatile Organic Constituents in Feed Materials

Volatile Constituent	Concentration (mg/kg) Soil	Spike[a]	Composite
Benzene	0.3	750,000	9,040
Ethylbenzene	0.3		1,300
Toluene	0.1		510
Total xylenes	0.5		410
Acenaphthene	150		690
Acenaphthylene	60		3,250
Anthracene	130		2,390
Benz(a)anthracene	90		1,470
Benzo(g,h,i)perylene	40		6,300
Benzo(a)pyrene	90		1,280
Chrysene	100		1,750
Fluoranthene	190		2,910
Fluorene	120		1,810
Indeno(1,2,3-cd)pyrene	30		480
2-Methylnaphthalene	170		7,070
Napthalene	130	250,000	13,500
Phenanthrene	340		7,470
Pyrene	250		4,100

Notes:
a = Only benzene and naphthalene were spiked
mg/kg = Milligrams per kilogram

(3) Decreased flue gas CO emissions

(4) Decreased flue gas NO_x emissions

(5) Decreased flue gas soot emissions

(6) Decreased combustion air requirements

(7) Decreased auxiliary fuel requirements

Test data addressing items (1), (6), and (7) are presented in Table 12. Data in this table represent the average of three tests at each test condition. Data show that the kiln exit gas temperature tested for all conditions averaged close to the test program target of 1,700°F (927°C) and that average afterburner exit gas temperature was right at the test program target of 2,000°F (1,090°C).

For Test Condition 1, the target waste feedrate was 61.1 lb/hr (27.8 kg/hr). This feedrate was increased to a target of 74.7 lb/hr (33.9 kg/hr) to give the borderline acceptable operation associated with Test Condition 2. Test Condition 3, with the pulse combustion system in operation, was targeted at the same feedrate as Test Condition 2, and the Test Condition 3 feedrate was 21% greater than the Test Condition 1 feedrate. An additional 13% increase in feedrate over the feedrate used in Test Condition 2 was possible before incinerator operation entered the borderline acceptable range with the pulse combustion system in operation. This resulted in a target feedrate of 84.0 lb/hr [38.2 kg/hr] for Test Condition 4. These test data show that a capacity increase of at least 13% (comparing Test Condition 4 to Test Condition 2) can be realized. In addition, the feedrate for Test Condition 4 was 35% greater than that for Test Condition 1.

Data in Table 12 further show that the total system heat input needed to maintain target incineration temperatures was relatively constant for all four test conditions at about 2.2 million Btu/hr (645 kW).

In addition, the auxiliary fuel requirements for Test Conditions 2 and 3 were nominally the same. Because auxiliary fuel use was relatively constant, the test data do not support the Sonotech claim that decreased auxiliary fuel use would be possible with the application of pulse combustion. However, because the waste treated in these tests had significant heat content, the capacity increase noted above equates to a corresponding decrease in the auxiliary fuel consumed per unit of waste treated. Comparing the auxiliary fuel consumption per unit of waste treated for Test Conditions 4 and 2 indicates that the feedrate increase allowed by the Sonotech system yields a corresponding decrease in auxiliary fuel use per unit of waste treated from 21,100 Btu/lb (52.5 megajoules per kilogram [MJ/kg]) to 18,000 Btu/lb (42.5 MJ/kg). Visual observations indicated that the Sonotech system produced improved mixing in the kiln chamber.

Data in Table 12 show that less combustion air was required for the two pulse combustion test conditions compared to conventional combustion test conditions. As the table shows, the combustion air requirements for Test Conditions 3 and 4 were lower than those for Test Conditions 1 and 2.

Test data addressing items (3), (4), and (5) are shown in Table 15. CEM data in this table represent the average of three tests at each test condition. Soot emission data represent the average for three tests at each test condition.

Data in Table 15 show that average kiln exit CO levels substantially increased with pulse combustion, from 68 ppm for the two conventional combustion test conditions (1 and 2) to 117 ppm for Test Condition 3 and 153 ppm for Test Condition 4. This increase is consistent with the observations that pulse combustion caused increased kiln solids bed temperatures and decreased kiln ash residue quality (heating value) when comparing Test Condition 3 to Test Condition 2. These findings, also discussed in Appendix Case Study 4, suggest that pulse combustion caused a greater degree of waste feed organic content volatilization into the kiln combustion gas. The observation that kiln exit CO levels increased with pulse combustion suggests that the greater amounts of volatilized organics were not completely destroyed in the kiln.

Table 14. Concentrations of Metals in Feed Materials

Average Concentrations	Antimony	Barium	Beryllium	Chromium	Cadmium	Mercury	Lead
Tar, mg/kg	<20	<1	<0.03	<0.7	<0.5	<1.6	<10
Soil, mg/kg	<20	<30.6	0.93	33	0.75	1.6	27.4
Coal/Sludge, mg/kg	<20	658	1.17	26.4	0.8	<1.6	36.4
Composite feed, mg/kg	<19	<271	<0.8	<21	<0.7	<1.5	<25.3
Tar TCLP, mg/L	<0.03	0.45	<0.0003	<0.007	<0.004	<0.0002	<0.38
Soil TCLP, mg/L	<0.03	0.84	<0.0005	<0.007	<0.004	<0.0002	<0.07
Coal/Sludge TCLP, mg/L	0.08	0.56	<0.0003	<0.007	<0.004	<0.0002	<0.04

Notes:

mg/kg = Milligrams per kilogram
mg/L = Milligrams per liter
TCLP = Toxicity characteristic leaching procedure

Incineration system afterburners are specifically designed to complete the combustion process and destroy products of incomplete combustion (such as CO) in the kiln exit combustion gas. During the demonstration, average afterburner exit CO levels decreased to 15 ppm for Test Condition 1 and to 20 ppm for Test Condition 2. Compared to conventional combustion, pulse combustion produced slightly lower average afterburner CO levels. Test Condition 2 (with conventional combustion) and Test Condition 3 (with pulse combustion) both had the same nominal waste feedrate, indicating that pulse combustion decreased average afterburner exit CO emissions to 14 ppm. Even at the increased waste feedrate achieved with pulse combustion for Test Condition 4, afterburner exit CO levels were only marginally increased to 17 ppm, which is higher than the Test Condition 3 level but is still 15% lower than the Test Condition 2 level.

CO is the final incomplete combustion product in the series of reactions that converts the carbon in organic constituents to CO_2. One explanation for the lower afterburner exit CO levels under pulse combustion operation (compared to conventional combustion), while kiln exit levels were higher, may be that organic constituent combustion in the kiln was more complete under pulse combustion operation. More complete combustion of organic constituents can result in higher CO levels (the final incomplete combustion product), while other unburned hydrocarbon levels (including soot) would be decreased. In such cases, fewer incomplete combustion products enter the afterburner, reducing the afterburner's burden to complete the destruction process. This can result in lower afterburner exit CO levels.

The afterburner exit soot emissions data (measured as TOC in the afterburner exit particulate) show a consistent pattern in the demonstration tests. Soot emission levels given in Table 15 represent the average for each of three tests at each condition, with the exception of the level noted for Test Condition 1. The afterburner exit particulate was analyzed for TOC for only one Test Condition 1 test, so the Test-Condition 1 value in Table 15 reflects only the one measurement. Soot emission levels were less than 1.3 mg/dscm for Test Condition 1, the baseline, conventional combustion test condition. They were increased to 1.9 mg/dscm for Test Condition 2. However, for Test Condition 3, with pulse combustion at the same feedrate as Test Condition 2, soot emissions decreased to less than 1.0 mg/dscm. Even at the increased waste feedrate achieved for Test Condition 4, the afterburner exit soot emissions were 1.3 mg/dscm, which is less than that of Test Condition 2. Average baghouse exit particulate emissions, corrected to 7% oxygen , were 133, 124, 64, and 104 mg/dscm for Test Conditions 1 through 4, respectively.

Table 16 shows that afterburner exit and baghouse exit NO_x emissions were comparable from test condition to test condition.

Although the data confirm the Sonotech claim that pulse combustion decreases NO_x emissions, the reductions achieved were small and originated from low initial NO_x levels.

DRE test data for benzene and naphthalene, the two test program POHCs, are given in Table 17. POHC feedrate values shown in the table result from combining the test waste feedrate measured for each test (see Table 12) with the waste feed POHC concentration (see Table 13). The POHC emission rate values noted in Table 17 were determined by combining flue gas flow rate data at each sample location for each test with the flue gas POHC concentration measured by the respective flue gas sampling procedure.

Naphthalene DREs measured at both the afterburner exit and the baghouse exit were uniformly 99.999% or greater for all tests and were not affected by different test conditions or different waste feedrates. Benzene DREs measured at the two locations also were not affected by different test conditions and were typically 99.994% or greater (with one baghouse exit benzene DRE measurement was 99.989%).

The average naphthalene emission rate at the afterburner exit was reduced from 1.2 mg/hr for conventional combustion at Test Condition 2 to 1.1 mg/hr with the Sonotech system at Test Condition 3. The average benzene emission rate at the afterburner exit was reduced from 7.7 mg/hr for Test Condition 2 to 5.7 mg/hr

Table 15. Summary of Gaseous Emissions Data

Test Condition	1	2	3	4
Kiln Exit				
O_2, %	11.3	11.1	10.5	10.7
CO, ppm	47.1	48.3	87.7	111.1
CO @ 7% O_2, ppm	67.9	68.0	117.1	153.4
Afterburner Exit				
O_2, %	9.3	9.3	8.7	8.5
CO, ppm	12.8	16.2	12.7	16.0
CO @ 7% O_2, ppm	15.2	20.3	14.4	17.9
CO_2, %	7.8	8.0	8.4	8.6
TUHC, ppm	1.0	1.5	1.22	1.6
TUHC @ 7% O_2, ppm	1.2	1.8	1.4	1.8
Baghouse Exit				
O_2, %	11.2	10.8	10.7	10.6
CO_2, %	6.1	6.5	6.4	6.7
Stack				
O_2, %	12.2	11.9	11.8	11.8
CO, ppm	6.5	13.9	12.3	12.5
CO @ 7% O_2, ppm	10.4	21.3	25.6	19.0
Soot				
TOC %	<1.0[a]	1.6	<1.0	1.4
Emission rate mg/hr	<1,200[a]	1966	96	1,466
@ 7% O_2 mg/hr	<1.3[a]	1.9	0.9	1.3

Notes:
[a]Indicates result of one analysis as two samples were lost
ppm = Parts per million

Table 16. Nitrogen Oxides Emissions

Test Condition	Afterburner Exit NO_x Emissions	Baghouse Exit NO_x Emissions
1	90 ppm	88 ppm
2	82 ppm	85 ppm
3	77 ppm	78 ppm
4	78 ppm	72 ppm

Note: All values corrected to 7% oxygen
ppm = Parts per million

for Test Condition 3. The significance of these decreases is difficult to judge because both fall within the precision of the respective flue gas concentration measurement methods.

4.3.2.2 Secondary Objective

The demonstration's secondary objective was to develop additional data to evaluate whether the Sonotech system, compared to conventional combustion, (1) reduced the magnitude of transient puffs of CO and TUHC; (2) resulted in reduced incineration costs; (3) significantly changed the distribution of hazardous constituent trace metals in the incineration system discharge streams (including kiln bottom ash, scrubber liquor, and baghouse exit flue gas); and (4) significantly changed the leachability of the TCLP trace metals from kiln ash. Data developed in support of the secondary objective reveal the following:

- Test program CEM data indicate that the Sonotech system did not change the magnitude of transient puffs of CO and TUHC, with no increases or decreases.
- Section 3 of this document discusses potential cost savings associated with use of the Sonotech system.
- Table 18 summarizes trace metal distribution data from the demonstration test program. The data suggest that using the Sonotech system does not affect the distribution of beryllium, cadmium, or lead. The concentration of barium and chromium appear to be slightly decreased in scrubber liquor and measurably increased in the baghouse exit flue gas for the Sonotech system test runs.
- Table 19 summarizes trace metal concentration data in the TCLP leachates of incinerator feed in residual discharges. The data show that the test program waste feed, the kiln ash, and the scrubber liquor residual, for all test conditions, are not RCRA toxicity characteristic hazardous wastes. In addition, TCLP leachate trace metal concentrations were not affected by using the Sonotech system.

4.3.2.3 Other Emissions Data

This section discusses other emissions data collected during the demonstration.

VOC and SVOC Data

Kiln ash and scrubber liquor samples for each test were analyzed for the VOCs and SVOCs listed in Table 6. No VOC or SVOC constituent was detected in any kiln ash or scrubber liquor sample from any test, with the exception of benzene in a few cases. Detection limits for VOCs were 1 to 10 mg/kg in kiln ash, and 1 to 10 microgram per liter (μg/L) in scrubber liquor. Detection limits for SVOCs were 0.1 to 0.3 mg/kg in kiln ash, and 1 to 3 μg/L in scrubber liquor. Benzene was detected in the kiln ash samples from one Test Condition 2 test, from one Test Condition 3 test, and from all three Test Condition 4 tests; however, these levels were only slightly above the MDL of 1 mg/kg.

Dioxin and Furan Data

The IRF RKS baghouse exit flue gas was sampled for PCDD and PCDF emissions during all 12 test runs. Although various PCDD and PCDF congeners containing chlorine atoms at the 2, 3, 7, and 8 positions were detected during each test run, no 2,3,7,8-tetrachlorodibenzo-para-dioxin (2,3,7,8-TCDD) congener was detected. The detection limit for 2,3,7,8-TCDD, which is sample specific for this analysis, ranged from 2.37 to 7.56 picograms per sample.

The total PCDD and PCDF emission values for each test condition were calculated based on the 2,3,7,8-TCDD toxicity

Table 17. Summary of Test Program POHC DREs

	Benzene					Naphthalene				
	Afterburner Exit			Baghouse Exit		Afterburner Exit			Baghouse Exit	
	Feed Rate (mg/hr)	Emission Rate[a] (mg/hr)	DRE	Emission Rate[a] (mg/hr)	DRE	Feed Rate (mg/hr)	Emission Rate (mg/hr)	DRE	Emission Rate (mg/hr)	DRE
Condition 1										
Test 1	253,000	4.4	>99.99	<1.2	>99.99	378,000	6.2	>99.99	5.9	>99.99
Test 6	253,000	7.6	>99.99	2.1	>99.99	378,000	2.9[b]	>99.99	3.1[b]	>99.99
Test 10	244,000	14.8	>99.99	3.4	>99.99	364,500	<0.3	>99.99	2.5[b]	>99.99
Condition 2										
Test 2	298,500	9.0	>99.99	31.0	>99.98	445,500	2.6[b]	>99.99	6.0	>99.99
Test 7	307,500	2.1	>99.99	<0.9	>99.99	459,000	0.6[b]	>99.99	<0.3	>99.99
Test 11	289,500	12.0	>99.99	0.6	>99.99	432,000	0.4[b]	>99.99	3.5[b]	>99.99
Condition 3										
Test 3	289,500	6.9	>99.99	6.4	>99.99	432,000	2.5[b]	>99.99	2.4[b]	>99.99
Test 5	307,500	3.4	>99.99	1.5	>99.99	459,000	<0.3	>99.99	0.6[b]	>99.99
Test 9	307,500	6.7	>99.99	2.9	>99.99	459,000	0.5[b]	>99.99	1.6[b]	>99.99
Condition 4										
Test 4	343,500	10.4	>99.99	2.5	>99.99	513,000	0.6[b]	>99.99	1.4[b]	>99.99
Test 8	334,500	11.7	>99.99	<1.5	>99.99	499,500	0.5[b]	>99.99	2.2[b]	>99.99
Test 12	334,500	50.9	>99.99	1.1	>99.99	499,500	1.3[b]	>99.99	0.4[b]	>99.99

Notes:

[a]Average concentration of three pairs of M0030 VOST tubes
[b]Analyte detected below lowest calibrated level
\> = Greater than indicated DRE
< = Analyte below method detection limit
DRE = Destruction and removal efficiency
mg/hr = Milligrams per hour

Table 18. Metals Distribution Results

Average Concentrations	Barium	Berylium	Chromium	Cadmium	Lead
Kiln ash (mg/kg)					
Condition 1	70.0	1.5	56.0	<0.6	<16.5
Condition 2	85.0	1.3	33.0	<0.7	17.0
Condition 3	60.0	1.4	37.0	<0.5	<12.5
Condition 4	63.0	1.3	39.0	<0.5	<10.0
MDL	1	0.03	0.7	0.5	10.0
Scrubber liquor (Post-test) (µg/L)					
Condition 1	500	4	60	2	1123
Condition 2	800	7	300	3	1590
Condition 3	360	6	109	7	800
Condition 4	457	3	58	17	2110
MDL	2	0.3	0.1	7	1
Scrubber exit flue gas (µg/dscm)					
Condition 1	30	<0.1	7.0	<1.0	<11.0
Condition 2	20	<0.1	7.0	<1.0	<11.0
Condition 3	102	<0.3	34.0	<1.0	<12.0
Condition 4	103	<0.3	34.0	<1.0	<11.0
MDL	0.8	0.1	2.4	1.0	10.0
Composite feed (mg/kg)	<271.0	<0.8	<21.0	<0.7	<25.3
MDL	1	0.003	0.7	20.5	10

Notes: Antimony and mercury were not detected in any samples
< = Average value is below MDL
mg/kg = Milligrams per kilogram
MDL = Method detection limit
µg/dscm = Microgram per dry standard cubic meter
µg/L = Micrograms per liter

Table 19. TCLP Results of Feed, Ash, and Scrubber Liquor

	Barium	Beryllium	Chromium	Cadmium	Lead
Feed, mg/L					
Coal	0.56	<0.0003	<0.007	<0.004	<0.04
Soil	0.84	<0.0005	<0.007	<0.004	<0.07
Ash, mg/L					
Condition 1	0.30	<0.0003	<0.007	<0.004	<0.04
Condition 2	0.62	<0.0003	<0.007	<0.004	<0.04
Condition 3	0.50	<0.0003	<0.007	<0.004	<0.05
Condition 4	0.69	<0.0003	<0.007	<0.004	<0.06
Scrubber liquor, mg/L					
Condition 1	0.15	<0.0005	0.03	<0.006	0.7
Condition 2	0.20	<0.0003	0.03	<0.005	0.3
Condition 3	0.13	<0.0003	0.08	<0.004	0.4
Condition 4	0.13	<0.0003	<0.03	<0.012	0.9
Regulatory level (mg/L)	100	NR	5	1	5

Notes:
mg/L = Milligrams per liter
NR = Not TCLP regulated
< = Average value is below MDL

equivalency factors (TEF). The total emissions, based on the TEFs, are referred to as 2,3,7,8-TCDD equivalents (TEQ) and were calculated by two methods as various analytes were reported as "undetected." First, the nondetected analyte concentration was assigned the MDL, and, second, the analyte was assigned a value of zero. This calculation method brackets the true TEQ value. All calculated concentrations were also corrected to 7% oxygen. The TEQ values for all runs were very low with no clear distinctions noticed with the Sonotech system operating. Table 20 presents the PCDD and PCDF TEQ values.

Table 20. Average Dioxin and Furan Toxicity Equivalent Emissions (picograms/dscm)

	2,3,7,8-TCDD TEQ Value	
Test Condition	MDL	Zero
1	5.4	0.4
2	5.0	0.4
3	4.1	0.3
4	4.6	0.6

Notes:

dscm = Dry standard cubic meter
TEQ = Toxicity equivalency emission
MDL = TEQ calculated by assigning all nondetected PCDD and PCDF congeners the value of their respective detection limit
Zero = TEQ calculated by assigning all nondetected PCDD and PCDF congeners a value of zero

Particulate and Hydrogen Chloride Data

The IRF RKS stack was sampled to measure particulate and hydrogen chloride emissions for all 12 tests. These measurements were necessary to address the IRF operating permit requirements and were performed after the RKS state-of-the-art emission control system. The stack particulate emissions for the 12 tests ranged from less that 0.5 to 2 mg/dscm, corrected to 7% oxygen. These values were considerably below the maximum permitted 180 mg/dscm. There were no distinct variations in particulate loading between the different test conditions.

Chloride ion was not detected in any of the Method 5 sampling trains. The MDL for hydrogen chloride emissions for each test, when corrected to 7% oxygen, was equal to or less than 0.24 g/hr, considerably less than the IRF permitted level of 500 g/hr.

Ash Quality Data

Kiln ash quality, measured as the kiln ash heating value, is presented in Table 12. With the Sonotech system operating under optimal test conditions (Test Condition 3), the heating value of the residual kiln ash was below detection limits.

4.3.3 Data Quality

The overall project QA objective was to produce well-documented sampling and analytical data that are reproducible and defensible. This objective was met by establishing precision, accuracy, method target reporting limit (TRL), completeness, and comparability goals. Data were evaluated with respect to these project goals. During the demonstration, the field team collected QA/QC samples—including matrix spike and matrix spike duplicate (MS/MSD) samples, field blanks, trip blanks, and equipment blanks. Laboratory QC samples were also analyzed to assure that data quality and proper procedures were used. Data quality indicators were calculated in accordance with established equations. Representativeness was assessed by evaluating the relative percent difference (RPD) values calculated from the duplicate samples and by evaluating the concentrations of interferences detected in the field and laboratory QC blanks. Based on an evaluation of these factors, the samples collected are considered representative of the media sampled.

QC checks and procedures were an integral part of the Sonotech demonstration to ensure that the QA objectives were met. QC checks and procedures focused on (1) the collection of representative samples without external contamination, and (2) the analysis of comparable data. Three kinds of QC checks and procedures were conducted during the demonstration: (1) checks controlling field activities, such as sample collection and shipping; (2) QC procedures associated with the field measurements; and (3) checks controlling laboratory activities, such as extraction and analysis. After a review of the QC results, 100% of the data from this demonstration is useable.

4.3.4 Conclusions

To achieve the demonstration objectives, tests were performed in triplicate at four different incineration system operating conditions, for a total of 12 individual tests. The four test conditions included the following:

- Test Condition 1, conventional combustion at typical operating conditions
- Test Condition 2, conventional combustion at its maximum feedrate
- Test Condition 3, Sonotech pulse combustion at the maximum feedrate for conventional combustion (the same nominal feedrate as Test Condition 2)
- Test Condition 4, Sonotech pulse combustion at its maximum feedrate

Data collected during the Sonotech SITE demonstration were evaluated using the rank sum test. The rank sum test allows the user to assess whether observed differences in data sets are statistically significant. When comparing two data sets, each containing three data points, the two data sets are different at the 95% confidence level when there is no data overlap. Unless noted, all conclusions are based on comparison of the average results from Test Condition 3 to the average results from Test Condition 2. The following conclusions may be drawn about the benefits of the Sonotech system:

- The Sonotech system increased the incinerator waste feedrate capacity by 13% compared to conventional combustion when comparing Test Condition 4 to Test Condition 2. The capacity increase was equivalent to reducing the auxiliary fuel needed to treat a unit mass of waste from an average of 21,100 Btu/lb (range of 21,000 to 21,300) for conventional combustion to 18,000 Btu/lb (range of 16,600 to 19,000) for the Sonotech system. Visual observations indicated improved mixing in the incinerator cavity when the Sonotech system was operating.

- Benzene DREs for all 12 test runs were greater than 99.994%. The Sonotech system reduced the average benzene emission rate from 7.7 mg/hr (range of 2.1 to 12) to 5.7 mg/hr (range of 3.4 to 6.9) at the afterburner exit.

- Naphthalene DREs were greater than or equal to 99.998% for all test runs. The Sonotech system reduced the average naphthalene emission rate from 1.2 mg/hr (range of less than 0.3 to 6.2) to 1.1 mg/hr (range of less than 0.3 to 2.5) at the afterburner exit.

Other demonstration results, comparing test conditions with the same nominal feedrate, are summarized as follows:

- The average afterburner CO emissions, corrected to 7% oxygen, decreased from 20 ppm (range of 8.0 to 40.0) with conventional combustion to 14 ppm (range of 12.6 to 16.0) with the Sonotech system.

- The average afterburner NO_x emissions, corrected to 7% oxygen, decreased from 82 ppm (range of 78.3 to 85.1) with conventional combustion to 77 ppm (range of 68.0 to 87.1) with the Sonotech system.

- Average afterburner soot emissions, measured as TOC and corrected to 7% oxygen, were reduced from 1.9 mg/dscm (range of less than 0.9 to 2.7) for conventional combustion to less than 1.0 mg/dscm (range of less than 0.8 to 0.9) with the Sonotech system.

- Total system combustion air requirements, determined from stoichiometric calculations, were lower with the Sonotech system in operation. The ranges for these values were 38,400 to 40,600 dscf/hr without the Sonotech system and 34,800 to 39,900 dscf/hr with the Sonotech system operating.

- Total natural gas fuel requirements (including kiln and afterburner) for all test conditions were similar. The total system average natural gas usage was 1,540 dscf/hr (range of 1,480 to 1,590) for conventional combustion and 1,580 dscf/hr (range of 1,520 to 1,620) for the Sonotech system at approximately the same feedrate.

Other general findings include:

- No substantial increase or decrease occurred in the frequency or magnitude of transient CO or TUHC puffs with the Sonotech system operating.

- Under the demonstration test conditions, use of the Sonotech system with the reported increase in incineration capacity can result in a cost savings. The reader is referred to the Economics section of this report to determine the approximate cost savings for a specific application.

- During the Sonotech demonstration, the Cello® combustion system caused no downtime and was judged to be reliable.

- Target metals investigated included antimony, barium, beryllium, cadmium, chromium, lead, and mercury. Their distribution in the discharge streams of the RKS did not vary significantly from test to test or from test condition to test condition except for barium and chromium. Concentrations of these two metals were slightly lower in the scrubber liquor and measurably higher in the baghouse exit flue gas when the Sonotech system was operating.

- The concentrations of target metals in the TCLP leachates were low to not detected in the feed, kiln ash, and scrubber liquor. At these concentrations, no significant test-to-test variations in the TCLP leachability of the various discharge streams were observed.

- No VOC or SVOC, other than benzene, were detected in any kiln ash or scrubber liquor samples.

- Dioxin toxicity equivalent values for all runs were very low and no clear distinctions were noticed with the Sonotech system operating.

- Stack particulate and hydrogen chloride emissions were very low with no distinct variations between different test conditions.

Section 5.0
Technology Status

5.1 Introduction

The Sonotech patented pulse combustion system has been developed to improve the performance of energy-intensive incineration and combustion processes. The primary component of the Sonotech system is the frequency-tunable Cello® pulse burner that operates over a range of frequencies. The Sonotech system includes a combustion section, the tuning device or "trombone," fuel and air systems, control and safety systems, a control panel, and a support structure.

In a typical application, the Sonotech system is retrofit and tuned to the process unit. Then it is operated at a combustion system-specific frequency that excites intense sound and turbulence within the process unit (see Figure 2). The intense sound waves and turbulence are designed to increase the rates of mass, momentum (or mixing), and heat transfer within the process, resulting in fuel savings, increased productivity, lower emissions, better product quality, and reduced maintenance. Sonotech claims that their system has been shown to improve the performance of both new and existing systems using conventional technology.

This section discusses the status of the Sonotech pulse combustion technology as well as the developer's experience in applying and retrofitting it to various industrial processes.

5.2 Completed Demonstrations

The SITE demonstration conducted at the IRF in Jefferson, AR, was the third application of Sonotech's system to an incineration process. The first and second demonstrations were both carried out under the EPA Small Business Innovative Research (SBIR) program at the EPA Air and Energy Engineering Research Laboratory (AEERL) in Research Triangle Park, NC. During the first demonstration, a bench-scale rotary kiln incinerator was retrofit with a frequency-tunable pulse combustion system to enhance combustion efficiency. The system excited large amplitude beneficial pulsations in the kiln and increased combustion efficiency by promoting better mixing conditions in the incinerator. The pulse combustor was operated in both steady state and pulsating modes. Tests were performed using two types of wastes:

1 Toluene sorbed onto a ground corncob sorbent placed in cardboard containers

2 Polyethylene (such as crushed milk jugs and styrofoam cups) placed in cardboard containers

During the second demonstration at AEERL, a second rotary kiln furnace simulator was retrofit with the Sonotech system, this second demonstration was designed to investigate whether the Sonotech system allows the incinerator to burn liquid hazardous wastes more efficiently than steady-state combustion.

The first two demonstrations were promising enough for the Sonotech technology to be selected for the SITE demonstration program. The SITE program demonstration at the IRF was also supported by the Industrial Gas Technology Commercialization Center of the American Gas Association.

The Sonotech system has also been applied commercially. From 1987 to 1994, Sonotech conducted applied research in cement pyroprocessing and applied an industrial-scale pulse burner on a vertical U-shaped precalciner at the Holman Cement plant in La Porte, CO. This project was sponsored by the Gas Research Institute (GRI) of Chicago, IL. The results of this program will be available for public review in late 1996.

From 1991 to 1994, Sonotech developed a retrofit application for a steel ladle preheater. The testing program showed that retrofitting a ladle preheater station with a pulse burner can improve the ladle's heating and reduce the ladle's specific heat consumption, that is, the amount of fuel needed to heat ladle refractories. Fuel consumption decreased by 9.2% with a corresponding hourly temperature increase of 33.5%. This project was cosponsored by GRI and Atlantic Steel.

In 1994 Sonotech installed at a confidential commercial site in California.

5.3 Ongoing Projects

Sonotech is currently working with Blue Circle Cement Company in Atlanta, GA to retrofit a rotary cement kiln with a Sonotech pulse combustion system. The retrofit application is expected to improve main burner flame pattern, improve heat distribution from combustion gases to the load within the kiln, and reduce pollutant emissions. The project is jointly sponsored by GRI, Columbia Gas Distribution Company, Southern Natural Gas Company, and Atlanta Gas Light Company.

Sonotech is also currently working with Centra-Union Gas of Ontario, Canada, to improve environmental emissions, improve heat transfer, decrease down time, and decrease the carbon content in the ash of large utility boilers. The demonstration project is scheduled to run from May to October 1996. Tests will be conducted at the Combustion and Carbonization Research Laboratory run by Natural Resources Canada.

Section 6.0
References

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Appendix
Case Studies

This Appendix summarizes claims made by Sonotech regarding the SITE Demonstration and the Sonotech frequency-tunable pulse combustion process. The information presented represents Sonotech's point of view; its inclusion in this Appendix does not constitute EPA approval or endorsement.

This Appendix provides four case studies of the application of the Sonotech frequency-tunable pulse combustion system in various energy-intensive and incineration processes. Case Study 1 describes the application of the Sonotech system in water spray evaporation experiments that simulated various aspects of the spray drying processes; Case Study 2 describes the application of the Sonotech system in limestone calcining, which is used in cement manufacturing and the pulp and paper industry; Case Study 3 describes the application of the Sonotech system in metal heating, which is used in metal reheating and melting furnaces; and Case Study 4 describes the application of the Sonotech system in incineration. Case Studies 1 through 3 were conducted by Sonotech, while Case Study 4 was conducted at the EPA IRF as a part of the EPA SITE Program in cooperation with Sonotech.

1.0 Case Study 1: Effect of Pulsations on Water Spray Evaporation

Case Study 1 was conducted by Sonotech between 1988 and 1989 under a contract entitled "Industrial Pulse Combustor Development and Its Application in Pulse Dryers," which was supported by the GRI. The study had two primary objectives:

- Demonstrate that pulsations excited by the Sonotech system can excite large amplitude pulsations in industrial-scale processes
- Demonstrate that such pulsations can increase the efficiency and productivity of water spray evaporation, which is one of the controlling processes in spray drying

This study was the first effort to demonstrate that pulsations can be used to increase the rates of mass, momentum (mixing), and heat transfer processes, all of which control the performance of most energy-intensive and incineration processes.

1.1 Program Description

This study was divided into two tasks. The first task investigated the effect of pulsations on the minimum amount of fuel required to completely evaporate a specific water spray flowrate in a cylindrical tank that simulated a spray dryer. The second task investigated the effect of pulsations on the maximum water spray flowrate that can be completely evaporated with a specific amount of fuel input to the spray dryer simulator. Both tasks are discussed below, followed by a discussion of test results.

1.1.1 First Task Test Setup

The first task of Case Study 1 was conducted in a horizontal cylindrical tank, 9 feet in diameter and 15 feet long. The tank simulated a spray dryer, and a set of spray nozzles on the tank was used to supply different water spray flowrates (see Figure A-1). The configuration and number of spray nozzles could be readily changed between tests. A Sonotech pulse combustion system was installed on the tank wall about 2 feet from one end. This system supplied the tank with a pulsating flow of hot combustion products that was directed tangentially to the inner tank wall. An exhaust duct installed at the opposite end of the tank was used to remove water vapor and combustion products from the tank. Water collected at the bottom of the tank was removed through an open drain at the bottom of the tank next to the Sonotech pulse combustor.

When the pulse combustor was operated at a frequency that equaled one of the natural acoustic modes of the tank, large-amplitude resonant pulsations were excited within the tank. The effect of these pulsations on the minimum amount of fuel required to completely evaporate a given water spray flowrate, supplied by a given arrangement of spray nozzles, was determined by repeating a given test with and without pulsations in the tank. Operators then noted the minimum amount of fuel required to completely evaporate the water injected into the tank by the spray nozzles.

A typical test was conducted by supplying the pulse combustor with a specific fuel flowrate. After conditions in the tank reached equilibrium, the water drain was inspected to determine whether water was leaving the tank. If this was the case, fuel input rate to the pulse combustor was increased, and the water drain was inspected again for the presence of water. This procedure was repeated until the pulse combustor fuel input rate reached a value that produced no water leaving the tank through its drain line, which indicated that all injected water sprays were completely evaporated. For each test condition, this fuel flowrate was determined in steady and pulsating tests.

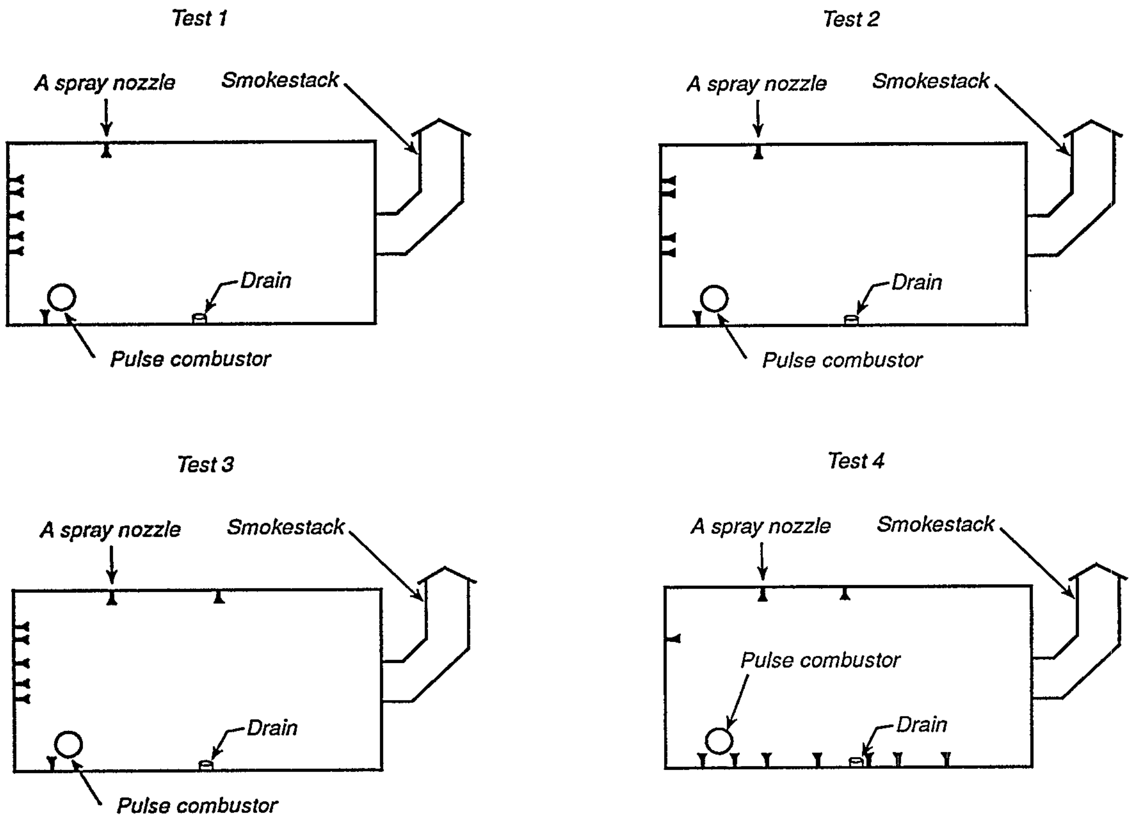

Figure A-1. A schematic of the spray nozzle configuration used in Task 1 to investigate the effect of pulsations upon water spray evaporation.

1.1.2 Second Task Test Setup

The second task of Case Study 1 was conducted in another spray dryer simulator that consisted of a vertical cylindrical tank, 7 feet in diameter and 12 feet long, connected to a 4-foot-long conical section at its base (see Figure A-2). Two spray nozzles installed in the middle of the top of the tank were used to inject a water spray into the system. The conical section had an opening at its apex through which water could leave the dryer simulator. A tunable pulse combustor was installed concentrically in a larger diameter pipe used to supply a pulsating flow of hot combustion products into the tank. The larger diameter pipe supplied dilution air to the dryer simulator. The dilution air was heated as it came in contact with the outside walls of the pulse combustor before it entered the dryer simulator. By changing the dilution air flowrate, the temperature and velocity distributions within the dryer simulator could be changed.

For these tests, the pulse combustor was operated with a fixed fuel input rate of 500,000 Btu/hr, while the dilution air flowrate was changed between tests. Each test was started by supplying the tank with a water spray flowrate that did not completely evaporate within the tank, resulting in an outflow of water through the hole at the bottom of the conical section. Next, the water spray flowrate was slightly decreased, lowering the water flowrate leaving the tank. This process was repeated until water stopped flowing out of the tank, indicating that the water spray was completely evaporated within the tank. For each dilution air flowrate, this test procedure was repeated with and without pulsations in the dryer simulator, and the water spray flowrate that was completely evaporated in each test was determined. The resulting flowrate is the maximum amount of water that can be completely evaporated in the tank under the investigated test conditions.

1.2 Test Results

The results of the tests conducted as part of the first task are summarized in Table A-1. Table A-1 provides information on the minimum pulse combustor fuel input rate, the total spray water flowrate into the tank, the oxygen concentration in the exhaust gas, the frequency and amplitude of the pulsations in the tank, the temperature of the exhaust gases, the "evaporation efficiency," and the percentage increase in "evaporation efficiency" when pulsations were excited in the tank.

For all four spray nozzle configurations, the temperature of gases in the exhaust stack was significantly lower when pulsa-

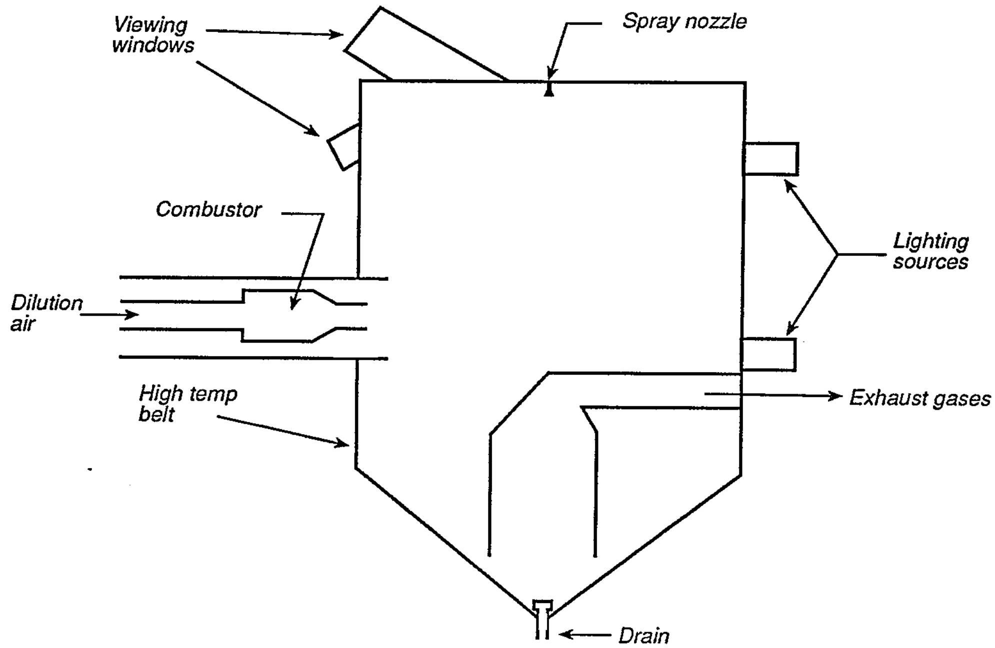

Figure A-2. A schematic of the evaporator setup used in Task 2 to investigate the effect of pulsations upon water spray evaporation.

Table A-1. Evaporation Efficiencies for Task 1

Test Number	M_f (MBtu/hr)	M_{water} (lb/hr)	Percent O_2	Frequency (Hz)	P_d (mV)	T_{ss} (°F)	Efficiency (Btu/lb)	Percent Increase in Efficiency Due to Pulsations
1a	4.5	1,863	7.2	90	1	575	2,415	
1b	3.75	1,863	7.9	76	20	478	2,013	16.67
2a	4	1,743	7.4	90	1	565	2,295	
2b	3.5	1,743	7.2	77	15	490	2,008	12.50
3a	4.5	2,134	7.2	90	1	578	2,109	
3b	4.15	2,134	7.9	77	15	495	2,185	7.78
4a	4.25	1,983	8.5	90	1	535	2,143	
4b	3.75	1,983	8.4	75	15	441	1,891	11.76

Notes:

Evaporation efficiencies were measured during complete evaporation of sprays in Task 1 tests conducted under nonpulsating (Tests 1a, 2a, 3a, and 4a) and pulsating (Tests 1b, 2b, 3b, and 4b) conditions in the spray configurations shown in Figure A-1.

M_f = Minimum fuel flowrate necessary to completely evaporate the water spray in million British thermal units per hour (MBtu/hr)
M_{water} = Water spray injected into evaporator in gpm
Percent O_2 = Percent oxygen in the exhaust flow
Frequency = Frequency in cycles per second Hertz (Hz)
P_d = Amplitude of pulsations inside the evaporator in millivolts (mv)
T_{ss} = Temperature of exhaust gases in the stack in Fahrenheit (°F)

tions were excited in the tank. Because the oxygen concentration of exhaust gases in pulsating and nonpulsating tests was almost the same, the lower exhaust flow temperature in pulsating tests strongly suggests that a larger fraction of the energy supplied by the Sonotech system was used to evaporate the water spray. The last column in Table A-1 shows that the pulsations significantly reduced the minimum amount of fuel required to completely evaporate various water spray flowrates in all of the investigated test configurations by amounts that varied between 7.78% and 16.67%. These results show that pulsations increased the thermal efficiency of the water spray evaporation, suggesting that resonant pulsations could produce significant fuel savings in a variety of drying processes.

The results of the second task are presented in Table A-2. Table A-2 provides data on results obtained in a series of tests in which the dilution flowrate was varied between 6,000 and 18,000 ft^3/min. Two tests were conducted for each dilution air flowrate with and without pulsations in the dryer simulator. The data show that for all tests, pulsations increased the maximum amount of water flowrate that could be completely evaporated with 500,000 Btu/hr fuel input to the combustor. These increases varied between 4.8% and 17.2%, and they indicate that the pulsations increased the productivity of the dryer simulator. These results are consistent with those obtained in the first task of this study (see Table A-1), and the observed increases in dryer simulator productivity indicate that the pulsations reduced the amount of fuel required to evaporate a unit mass of water spray flowrate. The results of this task also indicate that pulsations could be used to increase the capacity of a given dryer. Because it is expensive to increase the drying capacity of a given plant by acquiring a new dryer, the results of Case Study 1 indicate that the drying capacity of an existing plant could be increased more economically by retrofitting the dryer with a Sonotech pulse combustor.

Table A-2. Task 2 Maximum Water Flowrates to Completely Evaporate Water

Dilution Air Flowrate (dscf/hr)	Maximum Water Flowrate (lb/hr)	Pulsations (yes/no)	Percent Increase Due to Pulsations
6,000	290.4	yes	10.7
6,000	262.3	no	
11,000	295.1	yes	14.5
11,000	257.6	no	
13,000	318.5	yes	17.2
13,000	271.1	no	
18,000	304.5	yes	4.8
18,000	290.4	no	

Notes:
Fuel Flowrate = 500,000 Btu/hr
Combined Air Flowrate = 6,250 dscf/hr
Resonance amplitude in evaporator during pulsations = 149 dB
dscf/hr = dry standard cubic feet per hour
lb/hr = pounds per hour
Btu/hr = British thermal units per hour
dB = decibel

2.0 Case Study 2: Effect of Pulsations on Limestone Calcination

Limestone calcination, which involves the decomposition of calcium carbonate ($CaCO_3$) into calcium oxide (CaO) and CO_2, is an endothermic reaction used in many energy-intensive processes such as cement clinkering, light weight aggregate production, the pulp and paper industry, and flue gas desulfurization. Calcination consists of heating a limestone powder and removing the released CO_2, a process similar to the heat addition and moisture removal processes that control drying processes.

The effect of pulsations on limestone calcination was investigated in two different studies. In the first series of tests, large pieces of limestone with initial weights of about 360 grams each were calcined in a duct attached to the tail pipe of a small pulse burner capable of operating either in a steady or pulsating mode. The limestone was calcined at a temperature of 1,800 °F in both pulsating and steady-state tests, and calcination rates were determined by periodically removing and weighing the calcining limestone samples. The measured limestone calcination rate is presented in Figure A-3. The slopes of the two plots describe the calcination rate and show that the pulsations considerably increase the limestone calcination rate. Because calcination is controlled by the rates of heat transfer to and CO_2 transfer from the calcined particles, the test results indicate that pulsations increased the rates of these transport processes.

In the second series of tests, limestones of different initial weights were calcined as described above at a temperature of 1,720°F for 20 minutes under steady-state and pulsating operating conditions. The degree of calcination attained in each test was determined by weighing the limestone before and after the test. The percent weight losses obtained in the steady and pulsating tests are presented in Figure A-4. Because the data exhibited considerable scatter, data obtained in steady and pulsating tests were correlated on a computer, and the correlations are also presented in Figure A-4. The results show that pulsations increased the weight loss and increased the calcination rates of particles of different sizes. These results also indicate that a given calciner could operate at a lower fuel input rate to attain a given rate of calcination. These conclusions suggest that the productivity and thermal efficiency of a calciner can be increased by retrofitting the process with a Sonotech pulse combustion system.

3.0 Case Study 3: Effect of Pulsations on Metal Heating

Case Study 3 investigated the effect of pulsations on the heating rate of a stainless-steel cylinder. The study was performed to determine the influence of pulsations on metal heating. The potential applications of this process include ferrous and nonferrous metals production and metal reheating. The tests were conducted in the experimental setup used in Case Study 2.

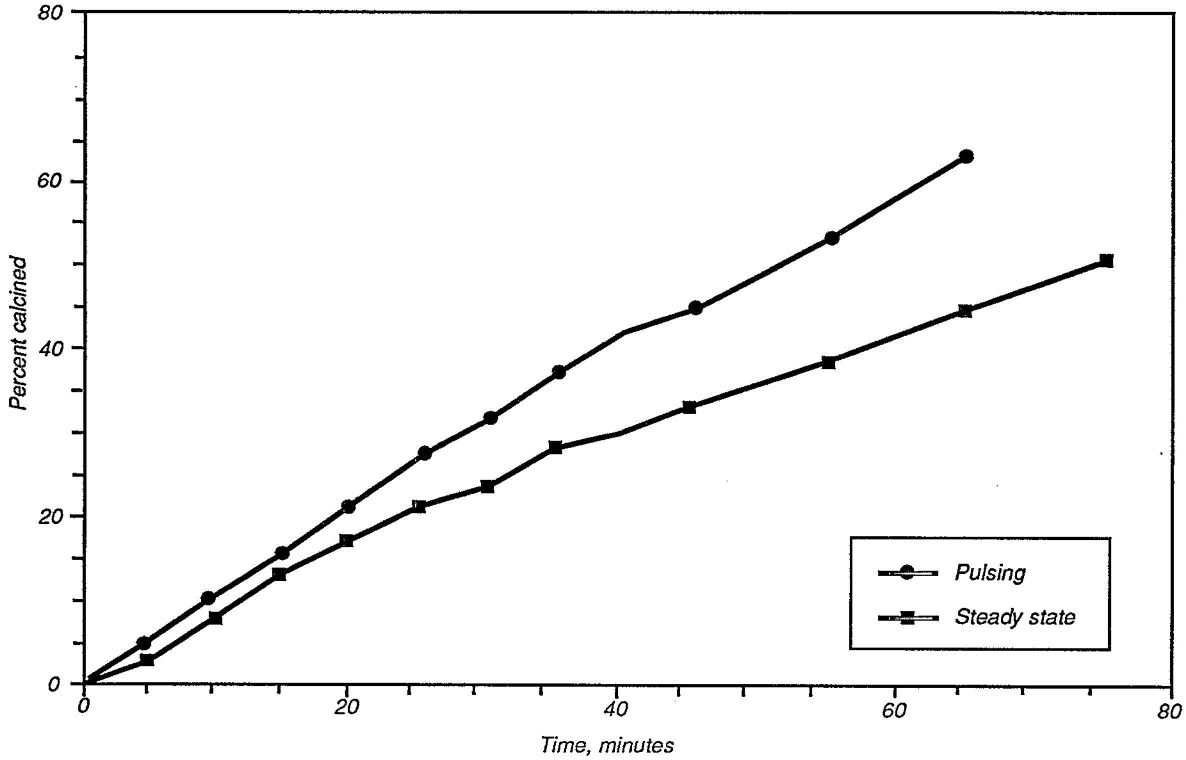

Figure A-3. Comparison of limestone calcination rates attained in 1800°F pulsing and steady-state flow tests.

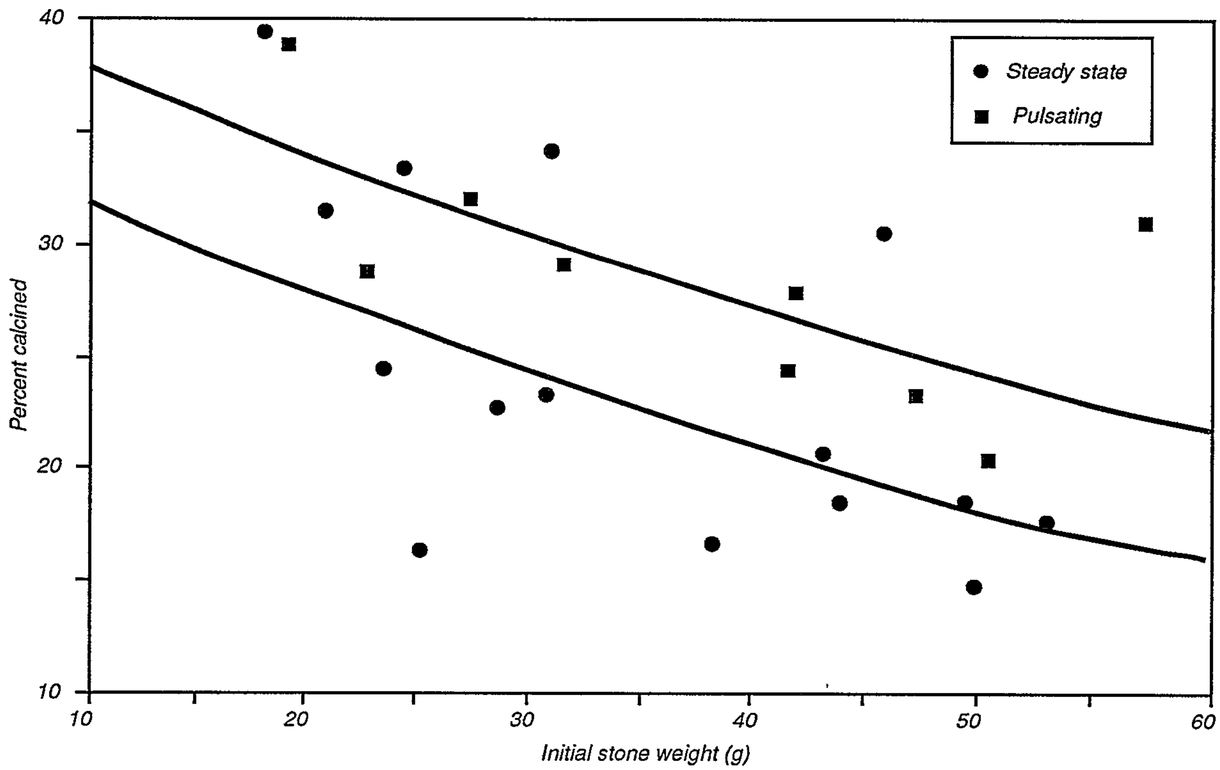

Figure A-4. Percentages of calcination attained by limestone having different initial weights in 20 minute steady and pulsing test at 1720°F.

3.1 Experiment Description

A stainless-steel cylinder, 3.5 inches in diameter and 7 inches long, was placed in the tailpipe of a pulse burner. A thermocouple installed at the center of the cylinder was used to measure the time dependence of the temperature in the cylinder. A second thermocouple was used to measure the gas temperature just upstream of the heated cylinder.

3.2 Tests Results

The effect of pulsations on the rate of heating the stainless-steel cylinder was determined by comparing the measured rates of temperature increase at the center of the sample. In each of the two tests conducted, the cylinder was heated in the same temperature gas in both pulsating and steady-state conditions. The heating rates measured in these tests are presented in Figure A-5. The results show that maximum temperatures of 1,417°F and 1,353°F were reached in the center of the sample in pulsating and steady-state conditions, respectively, indicating that the sample can be heated to a higher temperature in a pulsating environment. Figure A-5 also shows that pulsations measurably reduced the time required to heat the sample to a specific temperature. The sample was believed to be heated to a higher temperature in the pulsating test because the oscillations decreased the thermal resistance between the hot gas and the sample surface, resulting in higher convective heat flux to the sample and sample surface temperature. These results suggest that pulsations increase the fraction of input energy transferred to the heated metal sample and reduce the heating periods, indicating that retrofitting a metal heating process with a Sonotech system will produce fuel savings and will increase productivity.

4.0 Case Study 4: Effect of Pulsations on the Rotary Kiln Incineration of Superfund Waste

Scoping tests were performed at the EPA IRF in Jefferson, AR, to establish optimal operating conditions for incineration of wastes for the Sonotech SITE demonstration in the IRF RKS. The waste used in the scoping runs discussed in this case study consisted of coal, coal tar, and contaminated soil collected at the abandoned Peoples coal gasification plant, a Superfund site located in Dubuque, IA. During these scoping runs, the RKS was co-fired with toluene to stimulate the formation of puffs during the incineration of a hazardous waste. Because the amount of waste remaining after the scoping runs was not sufficient for the planned demonstration test runs, the waste was mixed with another waste for the subsequent demonstration test runs. Test conditions for the scoping test runs were similar to those discussed in Section 4 of this ITER. The scoping tests performed for the SITE demonstration are presented as Case Study 4.

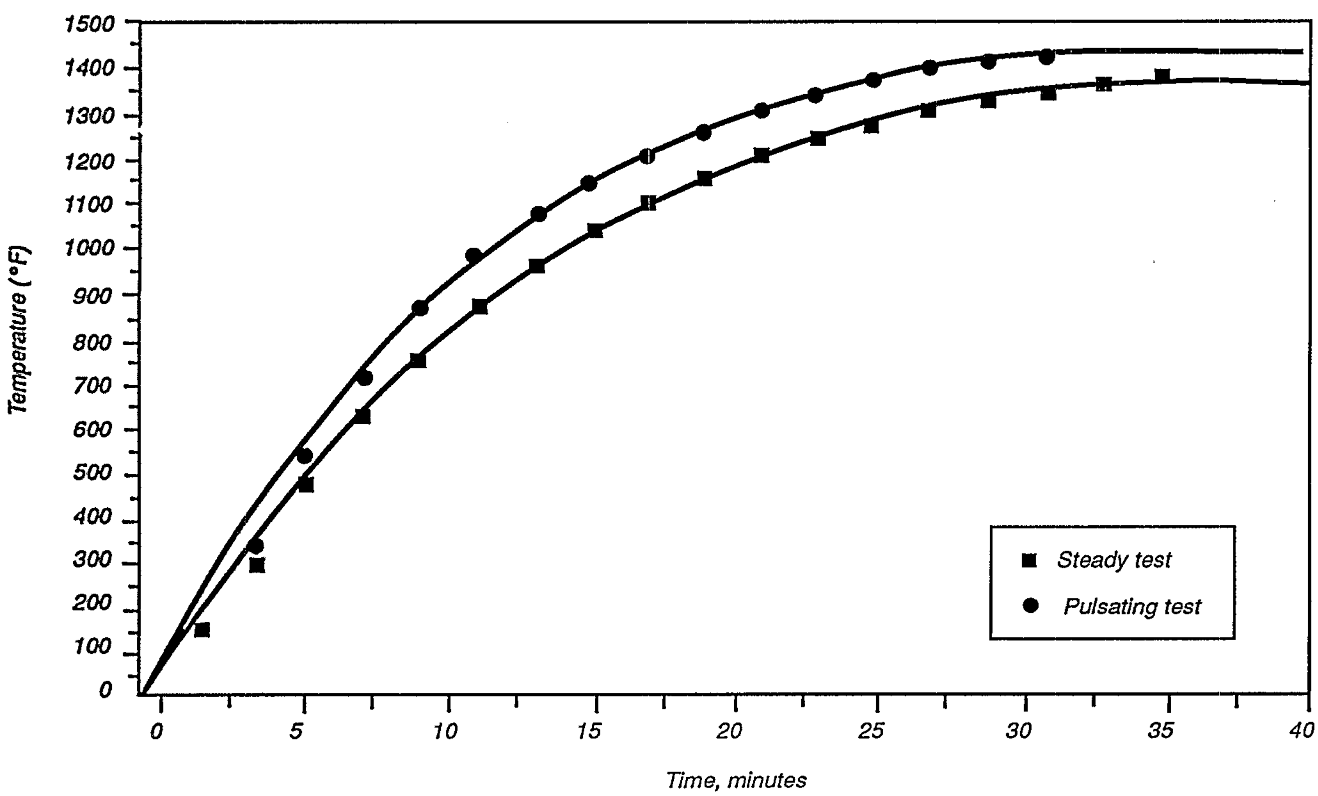

Figure A-5. Temperature rise at the center of the cylinder under pulsating and steady heating conditions.

4.1 Sonotech System Installation

Sonotech's pulse combustion burner system was delivered to the EPA IRF in Jefferson, AR, on April 19, 1994. The system was inserted through a 15-inch, outside diameter opening in the rear wall of the incinerator's primary combustion chamber. The Sonotech burner was mounted on special mounting rails, allowing the installation or removal process to take only 20 minutes. After completing a pulsating test, the Sonotech burner was removed, and a door over the opening was securely tightened.

4.2 Test Results

The incinerator waste feedrate was the key parameter in all tests. Both solids residence time and waste feedrate influence ash quality (that is, the quality of the incinerator's solid waste stream) and its emissions. The quality of the incinerator operation is determined by the ability of the incineration equipment to process wastes with appropriate residue quality and minimum emissions to the environment.

After completing the trial runs and during preliminary tests, the following changes were observed whenever the Sonotech system was in operation:

- The temperature inside the primary chamber increased (see Table A-3).
- The ash changed color from "charcoal black" to "gray."
- Videotape observations of the interior of the primary incineration chamber showed a highly intense burning process, which was apparently caused by improved mixing between the reactants and improved heat transfer to the waste.
- After the trial runs, melted ash residue was observed on the refractory surface. Such deposits could deteriorate refractory material and hinder program completion. To resolve

Table A-3. Summary of Data Measured in Sonotech Scoping Runs

Date	Test Conditions	Test 1 6/6/94	Test 2 6/6/94	Test 3 6/7/94	Test 4 6/9/94
Waste feedrate (lb/hr)		102.1	132.5	135	156
Co-fire, toluene (lb/hr)		9.8	8.3	6.8	8.0
Kiln speed (rpm)		0.09	0.09	0.09	0.094
Temperature (°F):					
	Kiln exit	1,550	1,570	1,620	1,550
	Afterburner exit	2,000	2,010	2,000	2,000
	Stack	156	161	171	175
Gas analysis (average):					
	Kiln exit: O_2, %	8.9	7.6	10.6	7.6
	CO, ppm	157	573	193	680
	Afterburner exit: O_2, %	9.3	8.3	7.6	8.0
	CO_2, %	8.0	8.9	8.3	9.2
	CO, ppm	10.5	39.2	7.0	46.8
	Stack exit: O_2, %	11.3	10.7	10.2	10.8
	CO, ppm	14.3	37.7	8.0	28.6
	NO_x, ppm	72.6	83	63	66.3
	TUHC, ppm	0.9	n/a	n/a	n/a
Main burner fuel consumption, dscf/hr		687	592	245	0
Main burner air flow, dscf/hr		14,920	14,020	10,360	13,820
Pulse burner fuel consumption, dscf/hr		0	0	200	200
Pulse burner air flow, dscf/hr		0	0	3,030	3,040
Afterburner fuel consumption, dscf/hr		1,050	950	1,000	900
Afterburner air flow, dscf/hr		7,920	7,420	7,940	7,900
Total fuel consumption, dscf/hr		1,740	1,540	1,450	1,100
Total fuel consumption per pound of waste, dscf/hr		17.0	11.6	10.7	7.1
Ash content, %		91	64	94	66
Ash heating value, Btu/lb		n/a	5,980	583	5,100

Notes:

O_2 = Oxygen
CO = Carbon monoxide
CO_2 = Carbon dioxide
NO_x = Nitrogen oxides
TUHC = Total unburned hydrocarbons
lb/hr = Pound per hour
rpm = Revolutions per minute
°F = Degree Fahrenheit
ppm = Parts per million
dscf/hr = Dry standard cubic foot per hour
Btu/lb = British thermal unit per pound
n/a = not analyzed

this problem, the operating temperature inside the incinerator's primary chamber was gradually reduced until no deposits were observed on the refractory surface.

These visual observations and recorded changes in monitored continuous emissions show that Sonotech system improved the rates of heat, mass, and momentum (mixing) transfer inside the primary chamber of the RKS. Results of ash test analyses on the heating value of the treated waste collected from the ash bin confirmed these observations.

Table A-3 presents data on the parameters monitored to characterize the operation and performance of the RKS during the two steady-state tests (Test Conditions 1 and 2, representing baseline and marginal incinerator operation, respectively) and two pulsating tests (Test Conditions 3 and 4, which are the Sonotech counterparts of steady-state Test Conditions 1 and 2, respectively).

4.3 Data Analysis

The data presented in Table A-3 represent averages of data collected by a fast data acquisition system. Table A-4 presents a comparison of results obtained in the steady and pulsating tests and shows the benefits produced by Sonotech's pulse combustion system. Equations depicting how observed benefits were calculated are shown and the terms in the equations are defined.

Table A-4. Benefits Provided by the Sonotech System

Waste feedrate increase (ΔG)	18% to 32%
CO emissions reduction (ER_{CO})	
Kiln exit	66%
Afterburner exit	82%
Stack exit	79%
NO_x emissions reduction (ER_{NOx}) at the stack	24%
Fuel savings (ΔB)	8.0% to 39%
Ash quality increase (ash heat content decrease) (θ)	90%

Waste Feedrate

The waste feedrate increase when the Sonotech system was operating was determined using the following equations and assumptions:

1. The waste feedrate increase attainable when the Sonotech pulse combustor is operated can be expressed as:

$$\Delta G = \{(G_4 - G_2)/G_2\} \cdot 100$$

where

ΔG = Percent increase in waste feedrate

G_i = Waste feedrate for condition i in lb/hr

2. Because incinerator operation under Test Condition 3 is considered "corrected to normal," it is logical to compare "normal conventional" to "normal pulsating" operation. The following formula was used to compute the increase in waste feedrate:

$$\Delta G = \{(G_3 - G_1)/G_1\} \cdot 100$$

Carbon Monoxide

Producing large amplitude beneficial pulsations inside the primary chamber of RKS allowed the main burner to be turned off, sustaining the incineration process for Test Condition 4 with the Sonotech burner operating as an acoustic mixer and burner. Such operation indicates that improved mixing, caused by pulsations, makes it possible to release more heating value from the waste. Additional increases in the waste feedrate were not possible due to the limited operating capabilities of the incinerator's feed conveyer. When the incineration system reached its physical limit, a waste feedrate of 156 lb/hr was accepted as the maximum value.

The effect of large amplitude beneficial pulsations to reduce CO emissions was computed using the following equation:

$$ER_{CO} = \{(CO_{cm2} - CO_{cm3})/CO_{cm2}\} \cdot 100$$

where

ER_{CO} = Percent reduction in CO emissions

CO_{cm2} = Averaged emission level of CO in ppm at the kiln exit, afterburner exit, and stack exit, obtained in Test Condition 2

CO_{cm3} = Averaged emission level of CO in ppm at the kiln exit, afterburner exit, and stack exit, obtained in Test Condition 3

Nitrogen Oxides

The percent reduction in NO_x emissions was obtained by comparing the averaged data from tests 2 and 3, because these tests were conducted at the same waste feedrate. The percent reduction in emissions of NO_x was determined as follows:

$$ER_{NOx} = \{(NO_{x2} - NO_{x3})/NO_{x2}\} \cdot 100$$

where

ER_{NOx} = Percent reduction in NO_x emissions

NO_{x2} = Averaged NO_x emission level in ppm under Test Condition 2

NO_{x3} = Averaged NO_x emission level in ppm under Test Condition 3

Fuel Consumption

Comparing the total system fuel consumption (including the main kiln burner, Sonotech burner, and afterburner) for Test Condition 3 to that for Test Condition 2 shows that, at the same waste feedrate, the Sonotech system allowed a fuel savings of 6.2%. In addition, the Sonotech system allowed a higher waste feedrate to be achieved under comparable operating conditions. Specifically, the waste feedrate achievable for Test Condition 4 was 15% greater than for Test Condition 2, under comparable incinerator operating conditions and with an ash product of comparable heat content. Furthermore, because the waste incinerated had significant heat content, the increase in feedrate corresponds to a decrease in the amount of fuel needed to incinerate a unit mass of waste. Specifically, the increased feedrate of Test Condition 4 corresponds to a 39% reduction in the Btu of fuel needed per pound of waste incinerated, when compared to Test Condition 2.

Incineration Quality

Incineration quality is measured by the heat content of the discharged ash. The increase in incineration quality was calculated by comparing data obtained from Test Conditions 3 and 2, because these two test conditions were performed at the same waste feedrate. The following equation was used to calculate the increase in incinerator quality:

$$\theta = \{(Q_{ash\,2} - Q_{ash\,3})/Q_{ash\,2}\} \cdot 100$$

where

θ = Percent increase in incineration quality

$Q_{ash\,2}$ = Average percent of heat content of the ash contained in the treated waste, obtained from Test Condition 2

$Q_{ash\,3}$ = Average percent of heat content of the ash contained in the treated waste, obtained from Test Condition 3

5.0 Conclusions

All data obtained in Case Studies 1 through 4 indicate that retrofitting an energy-intensive or incineration process with Sonotech's frequency-tunable pulse combustion system will improve the process and produce all or some of the following operating benefits:

- Reduced pollutant emissions
- Decreased auxiliary fuel requirement
- Increased process throughput
- Improved process and product quality

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